S
551.5271
N7osi
1979
c.1

RENEWABLE ENERGY
REPORT LIBRARY

STATE DOCUMENTS COLLECTION

MAY 1 0 1984

MONTANA STATE LIBRARY
1515 E. 6th AVE.
HELENA, MONTANA 59620

PLEASE RETURN

AN OVERVIEW OF THE SOLAR INSOLATION MEASUREMENT, MONTANA (SIMM) PROGRAM

Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

Ml.
84-23
13C
Wi Bird
HC

MONTANA STATE LIBRARY
S 551.5271 N7osi 1979 c.1 Fowlkes
An overview of the solar insolation meas
3 0864 00047520 5

AN OVERVIEW OF THE SOLAR INSOLATION MEASUREMENT, MONTANA (SIMM) PROGRAM

Prepared by

Charless Fowlkes
30 Gardner Park Drive
Bozeman, MT 59715

November 1977-April 1979

Prepared for

Montana Department of Natural Resources and Conservation
32 South Ewing, Helena, Montana 59620
Renewable Energy and Conservation Program
Grant Agreement Numbers 046-761; 084-772; 140-782

Available on loan from

Montana State Library, 1515 East Sixth Avenue
Justice and State Library Building, Helena, Montana 59620

This report was prepared under an agreement funded by the Montana Department of Natural Resources and Conservation. Neither the Department, nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information apparatus, product, or process disclosed, or represents that its use would not infringe on privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Natural Resources and Conservation or any employee thereof. The reviews and opinion of authors expressed herein do not necessarily state or reflect those of the Department or any employee thereof.

SIMM PROGRAM 1976-77, AN OVERVIEW

An overview of the SIMM Program is offered by the activity chart and the accompanying graph of expenditures in Figure 1. Major milestones were: (a) preparation and installation of instrumentation, (b) initiation of measurements, (c) initiation of computerized data reduction, and (d) preparation of the "Handbook of Solar Energy Experiments." The graph of expenditures shows a uniform flow of funds after the initial cost of the instruments. The project remained within the budget outlined in the original proposal.

A map, Figure 2, shows the location of the solar energy recording stations. The main solar energy data base comes from the 20 recording stations. About 5000 solar data-days have been accumulated at this writing. This data is represented and recorded in our computer file and consists of about 300,000 numbers representing solar intensities. Another computer file, containing reduced and integrated data, contains about 60,000 numbers. A summation of this data in terms of weekly and monthly averages is given in this report. This data can be used by the solar designer to calculate the energy output of his particular solar converison device. Particular examples of applications would include solar water heaters, residential and commercial solar heating or cooling systems, solar crop dryers, solar lumber drying kilns, and industrial process heat.

The SIMM Program makes use of volunteers at the public high schools to take care of the instruments and to mail the data to us for processing. There are about 50 volunteers across the state actively involved with this program. The volunteers are listed in Figures 3 and 4 along with their schools and locations.

The recording stations often locate the solar energy chart recorder in a classroom or laboratory room. Teachers have reported to us that observations of the solar energy records have been incorporated into their classes. Some classes have correlated weather observations and air pollution with the solar energy records.

The manual stations often use students to make the observations. This is done on a rotating schedule in which one student will be responsible for readings for a week or a day and then another student will take over. We feel that these students will gain considerable familiarity with the basic facts of solar energy through their participation with the program.

We estimate that several hundred students will have had some contact with solar energy measurement due to their participation with the SIMM Program this past year. We regard the solar insolation data itself as the primary goal of the SIMM Program and believe that this data will accelerate solar utilization in Montana. The involvement of the students and their exposure to solar energy phenomena may also contribute significantly, in the long run, to solar utilization.

The fact that we are dependent on volunteers means that we do not have the authority to enforce strict operational control over the data stations. We have lost some data due to power outages, school remodeling projects, and operational error. There were a few instances of damaged instruments and poor electrical connections which resulted in a temporary data loss.

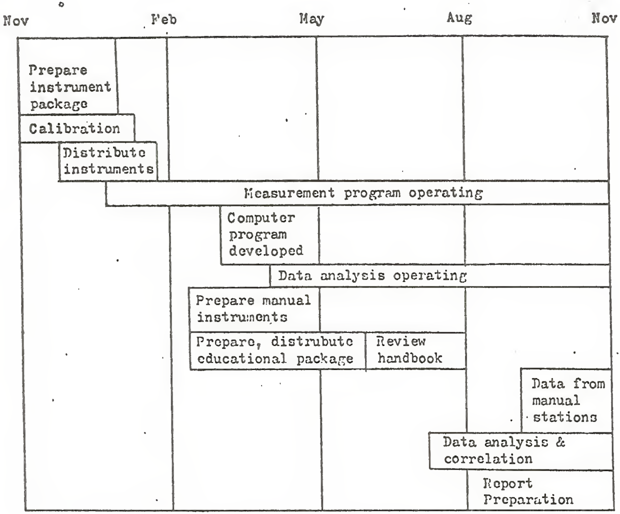
Total data lost from all stations for the entire year averages about 4 days per month per station. The added statistical uncertainty in the monthly averages due to a sampling of 87% (rather than 100%) is only a few percent. Thus, the average uncertainty due to lost data is well within the error band of the instruments themselves and the data reduction. A more detailed discussion of error is given in Appendices I and II.

Many of the stations have a nearly perfect record for monitoring the instruments and sending in data. The general level of cooperation of the volunteers has been, in my opinion, very high. I think many of the volunteers are aware of the energy crisis and recognize the importance of solar energy.

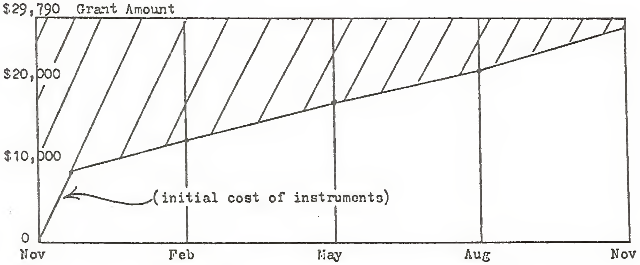
Certificates of Award were prepared toward the end of the first year's program. These are being sent to the volunteer teachers and their high schools. The recording stations received an award as shown in Figure 5. These were signed by John Orth and Thomas Judge as well as myself. Similar awards, signed only by me, were sent to the 30 manual stations. Initial reports indicate the success of this activity.

The solar insolation data in the next section is the main body of this report and represents the primary output of the SIMM Program. Technical discussion of the instruments and the data reduction are given in Appendices I and II. Appendix III covers new activities during the fourth quarter. Appendix IV contains a list of SIMM consultants.

Figure 1



Activity Chart for the SIMM Program



Graph of Expenditures during Grant Period

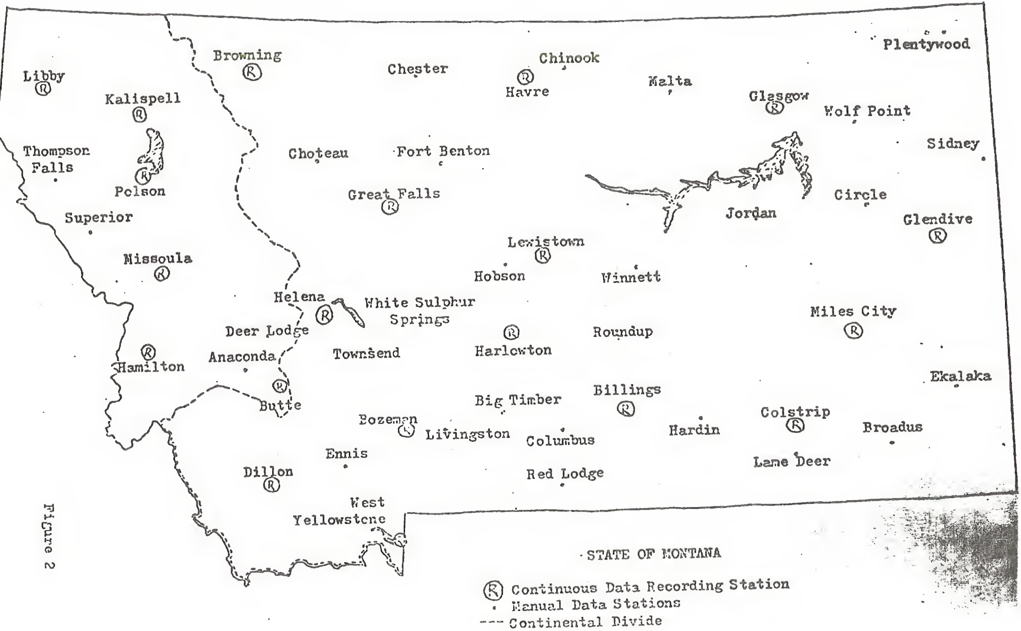

Plentywood
Browning
Chinook
Libby
Chester
Havre
Malta
Kalispell
Glasgow
Wolf Point
Thompson Falls
Choteau
Fort Benton
Sidney
Polson
Great Falls
Circle
Superior
Jordan
Glendive
Lewistown
Missoula
Hobson
Winnett
Helena
White Sulphur Springs
Miles City
Deer Lodge
Roundup
Harlowton
Townsend
Anaconda
Hamilton
Ekalaka
Billings
Big Timber
Butte
Colstrip
Bozeman
Livingston
Columbus
Hardin
Broadus
Ennis
Lame Deer
Dillon
Red Lodge
West Yellowstone
STATE OF MONTANA
Ⓡ Continuous Data Recording Station
• Manual Data Stations
--- Continental Divide

Figure 2

Figure 3: SIMM Participants, Recording Stations

Location	High School	Volunteer
Billings	Billings Senior	Mike Jablin
Bozeman	Bozeman Senior	Roscoe Montgomery
Browning	Browning	Jim Prestbo
Butte	Butte	Phil Foley
Colstrip	Colstrip	Dave Bowser
Dillon	Beaverhead	William Mular
Glasgow	Glasgow	Norm Girard
Glendive	Dawson County	Ed Helgeson (76-77) Richard Lindgren (77-78)
Great Falls	Charles M. Russell	Gary Shelden
Hamilton	Hamilton	Bill Delaney
Harlowton	Harlowton	John Schell
Havre	Havre	Avon Whitehead
Helena	Helena	Jim Haslip
Kalispell	Flathead	Gary Freebury
Lewistown	Fergus	Howard Cooper
Libby	Libby	Mike Funk
Miles City	Custer Co. District	Otto Neuhardt
Missoula	Hellgate	Norman Jacobson
Polson	Polson	Ted Macy
West Yellowstone	West Yellowstone	Warren George, Jr. (76-77) Scott Carsley (77-78)

Figure 4: SIMM Participants, Manual Stations

Location	High School	Volunteer
Anaconda	Anaconda	Bob Cossack
Big Timber	Sweet Grass Co.	Dick Willems
Broadus	Powder River Co.	Henry Eslinger
Chester	Chester	Marvin Krook
Chinook	Chinook	Gail Swant
Choteau	Choteau	Norman Kamrud
Circle	Circle	Robert Fitzgerald
Columbus	Columbus	Waymoth Fitzgerald, Jr.
Deer Lodge	Powell Co.	Gary Swant
Ekalaka	Carter Co.	Jane Claypool
Ennis	Madison Valley Cons.	Orville P. Hess
Fort Benton	Fort Benton	T. Daniel Gillen
Hardin	Hardin	Roland Croghan
Hobson	Hobson	Rick McIntyre
Jordan	Garfield Co.	Norman Ostby
Lame Deer	Lame Deer School	
Livingston	Park Senior	Ben Williams
Malta	Malta	Jeffrey Bredeson
Plentywood	Plentywood	Harold Gackle
Red Lodge	Red Lodge	Bob Holmen
Roundup	Roundup	Jim Schladweiler
Sidney	Sidney Senior	E. F. Krueger
Superior	Superior	Clark Conrow
Thompson Falls	Thompson Falls	Joni Keating
Townsend	Broadwater Co.	William Alley
White Sulphur Springs	White Sulphur Springs	Connie Perkins
Winnett	Winnett	Frank Witter
Wolf Point	Wolf Point	Arthur Sikkink

Fowlkes Engineering
Awards This

Certificate of Appreciation

To

Gary Shelden

And

Charles M. Russell High School

FOR THEIR CONTRIBUTION TOWARD MEASURING MONTANA'S SOLAR ENERGY RESOURCE THROUGH THE PROGRAM, SOLAR INSOLATION MEASUREMENT, MONTANA

John C. Orth
Director,
Montana Dept. of Natural Resources & Conservation

Thomas L. Judge
Governor,
State of Montana

Charles M. Fowlkes
Owner,
Fowlkes Engineering

SOLAR ENERGY DATA FROM SIEM PROGRAM

Introduction

ALL THE DATA IN THE FOLLOWING TABLES RELATES TO SOLAR INSOLATION FALLING ON A SURFACE FACING DUE SOUTH AND TILTED 60° UP FROM THE HORIZON. This orientation is nearly optimum for collecting heat energy during the winter heating season in Montana.

Total Insolation

The tables contain values of "total" insolation. These values result from the integration of the daily solar insolation curves. These values represent the "total energy" that fell on the surface of the transducer during the entire day. This value represents the maximum energy which could be recovered with a 100% efficient solar collector. (Real collectors have conversion efficiencies around 20-70%.)

Threshold Radiation

In addition to total radiation data, we are calculating the radiation above a series of thresholds. The reason for calculating threshold data derives from the operating characteristics of nearly all solar collectors.

A solar collector is normally operating only during periods of relatively high solar intensity, due to the losses inherent in any collector. In early morning or evening hours or during other periods of low radiation, if the circulation pump were on, a collector would lose more heat than it would gain. The radiation falling on the collector must be of an intensity great enough to raise the collector surface temperature above the temperature of the storage reservoir. A real collector will thus only capture a fraction of the total available insolation.

For example, if the storage reservoir has a temperature of 125°F and the ambient air is 25°, and if the collector is double-glazed, the heat loss through the glazing will be about 0.68 BTU/ft^2-hr-F$^\circ$ or about 68 BTU/hr-ft^2. Assume that additional conduction losses result in a total loss of 90 BTU/hr-ft^2. Thus, if the radiant intensity were less than this amount, the collector would operate at a net LOSS.

In recognition of this characteristic, the percentage of total radiation above a series of thresholds from 0.1 kW/m^2 to 1.2 kW/m^2, spaced 0.1 kW/m^2, is tabulated. Given the operating threshold of a particular collector, it is possible to interpolate the data to determine the energy available. This value is further modified by the collector efficiency to determine the actual energy which can be collected.

Accuracy

The average accuracy of the solar insolation data in these tables is ±5%. On individual days, especially overcast days, the uncertainty is greater, while on clear days the uncertainty is less. These uncertainties tend to average as the data itself is averaged. A more thorough discussion of the accuracy of the instruments and the data reduction process is given in Appendices I and II.

Missing Data

There are some time periods in the tables for particular stations for which no data was available. These voids were due to a variety of causes: instrument malfunction, electric power interruption, chart paper improperly installed, chart paper ran out (especially during the summer), remodeling of school building, power turned off during vacations, data lost by Post Office, etc. The tables contain the statement "No Data for This Period" when data was not available.

The solar designer is advised to estimate missing data by interpolating insolation values from nearby measuring stations. The map in Figure 2 will be helpful in identifying the closest recording stations.

Solar Insolation Data
Compiled By
Fowlkes Engineering
Bozeman, Montana 59715

Location: Billings, Montana

Sample

Interval	Daily KWH/SM	% Total Energy Above Threshold (KW/SM) >.1	>.2	>.3	>.4	>.5	>.6	>.7	>.8	>.9	>1.	>1.1	>1.2
Feb 1 to Feb 5	5.41	99	96	[illegible]	90	83	79	71	56	33	0	0	0
Feb 6 to Feb 12	4.55	93	87	84	79	70	64	56	40	23	1	0	0
Feb 13 to Feb 19	3.03	83	76	70	65	56	50	45	30	15	0	0	0
Feb 20 to Feb 26	3.76	72	67	[illegible]	60	55	49	43	33	24	2	0	0
Feb 27 to Feb 28	5.58	98	[illegible]	[illegible]	92	85	80	70	56	33	2	0	0
Month of Feb	4.20	[illegible]	82	78	74	66	61	54	40	24	1	0	0
Mar 1 to Mar 5	4.55	[illegible]	92	88	82	75	66	55	37	31	10	2	0
Mar 6 to Mar 12	3.94	[illegible]	[illegible]	78	68	60	52	43	34	13	7	1	0
Mar 13 to Mar 19	3.56	91	83	77	69	60	51	43	33	20	7	0	0
Mar 20 to Mar 26	[illegible]	[illegible]	[illegible]	74	72	66	58	49	36	23	7	2	0
Mar 27 to Mar 31	3.29	84	60	46	36	34	32	28	24	16	0	0	0
Month of Mar	3.95	[illegible]	81	73	66	60	52	44	33	20	6	1	0
Apr 1 to Apr 2	2.73	[illegible]	73	53	30	22	14	8	0	0	0	0	0
Apr 3 to Apr 9	[illegible]	[illegible]	88	83	77	71	65	57	46	26	4	1	0
Apr 10 to Apr 16	4.98	[illegible]	90	82	76	69	63	54	41	13	4	1	0
Apr 17 to Apr 23	4.01	83	77	67	61	55	49	40	27	9	3	1	0
Apr 24 to Apr 30	5.26	97	94	90	83	75	66	53	28	0	0	0	0
Month of Apr	4.73	93	86	79	71	65	58	48	33	11	2	0	0
May 1 to May 7	4.13	95	86	74	66	58	50	36	24	10	0	0	0
May 8 to May 14	4.92	95	92	84	77	68	60	47	20	0	0	0	0
May 15 to May 21	2.80	80	61	50	45	39	32	25	16	7	1	0	0
May 22 to May 28	3.96	94	86	76	67	58	51	39	15	2	0	0	0
May 29 to May 31	4.97	96	93	87	84	72	61	39	9	0	0	0	0
Month of May	4.05	92	82	72	66	57	49	37	18	4	0	0	0

SOLAR ENERGY DATA FROM MANUAL STATIONS

Introduction

Thirty high schools were instrumented with SIMM-1M manual solar energy instruments. The schools were asked to take at least one solar energy reading each school day, record it on a prepared chart, and send it to us each month for compilation. The instruments were distributed last May with the understanding that data would be collected starting with the beginning of school in September. Hysham and Scobey decided not to participate and the instruments will be reassigned.

The manual stations were instrumented with the assumption that the data would be considerably less reliable than data from the 20 recording stations. This is because the manual data is taken periodically rather than continuously and due to reading and orientation errors. Often different teachers and students take the data during the month.

Data

An example of the data sheets is shown in Figure 6. This is one of the more complete data sets we have received. To date about 25-30% of the stations have taken several readings during each day, about 25-35% have taken more than one reading, and about 12% have sent us only noon readings. We have not yet received data from 18% of the stations. The quality of the data seems to be improving as the personnel become more familiar with the instruments.

Data Processing

The hourly manual data is averaged over the month. These averaged values are plotted versus time of day. Zero points representing sunrise and sunset are added and a curve is drawn through all these points. This curve thus represents a monthly average insolation curve. The curve is integrated numerically to yield a value for average daily insolation.

Sample curves are shown in Figure 7. These illustrate the interpolation procedure for stations having a variety of data. The top curve is clearly more accurate due to the larger data base.

The average solar insolation data compiled from the manual stations during September and October are given in Table 1. Data from a few stations was clearly suspect due to improper orientation of the transducer or reading error and is omitted.

Conclusion

The manual portion of the program has involved a large number of students and teachers and is clearly a valuable solar educational exercise. The significance of the data will be evaluated at a later time as more data becomes available. It will be necessary to compare the manual data with nearby recording stations and with solar noon maximums to determine a statistically meaningful value for percentage accuracy or reliability. This will be done at the end of the school year. For the time being, the manual data should be classed as "preliminary data" because the absolute accuracy has not been determined.

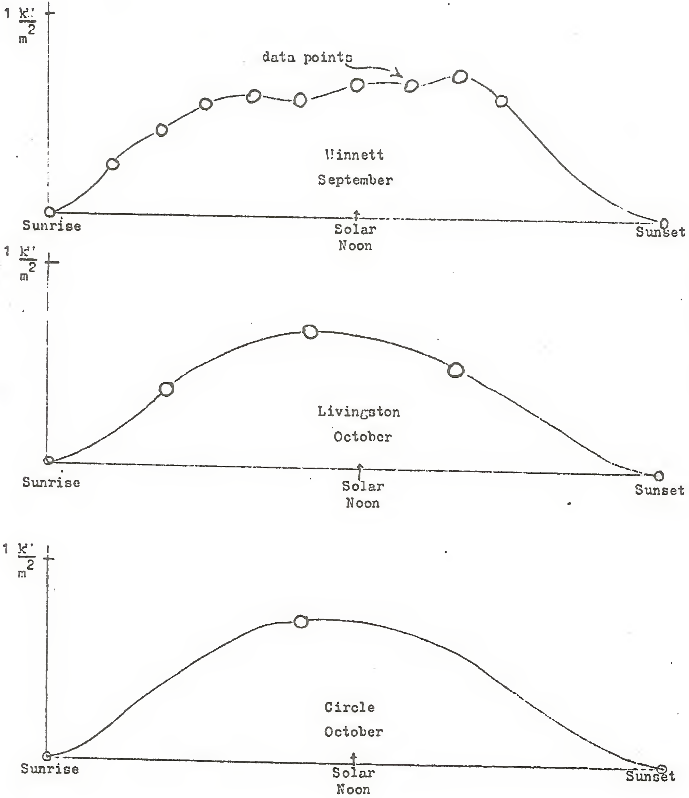


Figure 7: Examples of Monthly Average Solar Insolation from Manual Instrument Stations

Location	Average Daily Solar Insolation[t] (K'-hrs/m^2)	
	Sept	Oct
Anaconda	1.94*	3.03*
Big Timber	No Data Available	
Broadus	5.31*	5.10
Chester		3.89*
Chinook	4.24**	5.83**
Choteau	4.63	4.74
Circle	3.87*	5.17*
Columbus		4.82
Deer Lodge	4.10	5.15
Ekalaka	5.05**	6.15
Ennis	2.83	2.63*
Fort Benton		4.35**
Hardin	No Data Available	
Hobson	4.96**	4.38**
Jordan	No Data Available	
Lame Deer	No Data Available	
Livingston	4.91	5.18
Malta		5.61
Plentywood		5.41
Red Lodge		5.24**
Roundup	4.11*	5.39*
Sidney	3.03	5.62*
Superior	3.04**	
Thompson Falls	4.70**	5.46**
Townsend	6.67**	5.44**
White Sulphur Springs		4.02
Winnett	5.87**	5.64**
Wolf Point	5.05**	5.79**

* only one daily reading

** more than 4 daily readings

[t] This data should be considered preliminary data until its accuracy can be fully assessed.

Table 1: Average Daily Solar Insolation Data for Manual Stations, September and October, 1977

APPENDIX I:

TECHNICAL DISCUSSION OF SOLAR INSTRUMENTATION AND ACCURACY

Commercial Instruments

Reviews of currently used solarimeters and pyranometers are given by Blanco (1), Daniels (2), Haywood (3), and Majumdar (4). Instruments based on thermo-electric measurement, calorimetric measurement, and photovoltaic measurement are available. The best known and most widely used instruments are the Eppley and Kipp pyranometers. The Eppley, which is manufactured in the United States and commonly used here, consists of a blackened metallic receiver 3 cm in diameter surrounded by a white or silver outer ring. A copper-constantan thermocouple is attached to the blackened receiver with the cold junction attached to the reflective outer ring. The temperature difference between the black body and the reflective body gives a measure of the radiation. The reflective ring remains at nearly ambient temperature. The daily output of the thermocouple is measured by a recording pyranometer. This curve is then integrated to give total daily radiation.

The receiving surface is normally placed horizontally and covered by a hemispherical, transparent glass or plastic cover. The direct radiation as well as the diffuse radiation fall onto the surface and are recorded. Properly calibrated, the Eppley and Kipp pyranometers have an accuracy of ±5%.

Photovoltaic Instruments

Experiments have been performed to test the applicability of silicone photovoltaic cells for solar radiation measurements by Yellott (5), Schoffer, et. al. (6), Banner, et. al. (7), and Whillier (8). A commercial instrument, the Sol-A-Meter, is currently manufactured by Matrix, Inc., of Phoenix under a license from John Yellott.

The silicon cell consists of a p-n junction of ultra-pure silicon. Photons striking the cell cause electrons to be displaced, which is a current. Under proper loading conditions, the current flow is directly proportional to the incident radiation. This behavior makes the silicon cell a candidate for solar measurement.

The advantages of the silicon transducer are its relatively high electrical output and its long-term stability and reliability. Its disadvantages include a slight temperature dependence and a spectral sensitivity which departs from black body behavior. Extensive experiments are reported in the references above which compared standard Eppley and Kipp pyranometers with silicon cell pyranometers (5,7,8). These experiments show that the silicon instruments can produce results within ±5%. Most of the inaccuracy occurs when the sun is at low angles. The variation of calibration with optical path length is related to the spectral response of the cell. This effect may be seen in the calibration data for the SIMM instruments used in this program.

Instruments for the SIMM Program

Instruments based on the silicon cell transducer were chosen for use in the SIMM program for two reasons: (1) the overall cost of the instruments was minimized and (2) the characteristics of the transducer have been well documented. That is, the silicon cell measurements are related to the standard radiation instruments.

This second factor is very important. There are a large number of photovoltaic and photoresistive transducers available at the present time. Any of these devices, when connected to the proper circuit or meter, will give some change in output with variations in "light" intensity. The common Cd-S photographic light meter is an example. Due to linearity problems and spectral response, this system would not be useful for energy measurements.

The immediate purpose of the SIMM program is to make measurements which will accelerate the utilization of solar energy. It is therefore important that there be a direct relationship of the measurements made to the measurements needed for solar design. Since this relationship has been documented in the literature (5,6,7,8), no additional development or research programs are needed to establish "the meaning" of the measurements.

Prof. John Yellott has U.S. patents covering some aspects of solar measuring instruments using silicon cells. I have described the SIMM program and the instruments to him. He has assured me that the SIMM instruments (1) would not infringe on his patents and (2) would be quite accurate and easy to calibrate.

Description of the SIMM Instrument Package

The instrument package distributed to the high school measuring stations consists of two solar radiation measuring units, the SIMM-1 and the SIMM-1R. Photographs of the instruments are shown in Figure I-1.

SIMM-1 is a hand-held instrument. It consists of a silicon cell mounted on a tiltable plate. The plate is hinged to a small instrumentation box which contains the indicating meter. The instrument is self-powered and needs no batteries. It is used in this program as a back-up instrument and as an educational tool.

The SIMM-1R instrument incorporates a strip chart recorder so that a continuous record of solar energy can be obtained. The recorder drive is powered by 100 vac. The transducer is separate from the recorder and consists of a silicon cell mounted on an angled plate. This assembly is designed for attachment to an exterior wall or roof. The recorder is located inside the building on a convenient shelf or cabinet.

Transducer Orientation of SIMM-1R

The silicon cell in the SIMM-1R transducer will be mounted facing south and at an angle of 60 degrees from the horizontal. This orientation is chosen because it is nearly the optimum winter collection angle for Montana. The data taken at this angle can accurately be transformed to other similar angles. Weather bureau data records radiation on a horizontal surface. Transforming this data to practical collector angles produces error. (In Montana in the winter the altitude of the sun is about 20 degrees.) It is the philosophy of this program to make measurements which will implement the utilization of solar energy. This goal is achieved by taking the data at orientation matching the ultimate device.

Calibration and Error

Calibrations of the instruments were done by comparing the output of the prototype SIMM instrument with an Eppley pyranometer and a Kipp-Zonen pyranometer. These calibrations were performed with the SIMM instrument in the horizontal position, to match the orientation of the Eppley and Kipp. Eppley and Kipp instruments are probably the most common instruments used for solar energy measurement around the world and their performance is well understood. (See Figure I-2.)

The results of a calibration run for an entire clear day are shown in Figure I-3. The calibration results show that the SIMM can be calibrated to within a deviation of 1% during the middle part of the day. In the early morning and the late evening the deviation rises to 5-15%. This phenomenon is explained by the spectral response of the silicon cell and is well documented in the solar literature. These errors at the beginning and end of the day are not as large as they may seem because the absolute energy is low.

The error in total energy on this particular day is shown in Figure 11 to be less than 1%. Because the absolute accuracy of the Eppley and Kipp instruments is only about 5%, it can be seen that the SIMM instrument is well within this band of error.

Errors in Data Reduction

Data is read from the strip charts by hand by a single staff member. The average solar radiation over a 15-minute time interval is recorded as a two-digit number. Approximately 60 such numbers are read from each chart.

Some technical judgment is required to read the charts on days when there is mixed overcast. These curves are jagged and the rough curve must be averaged over the time interval.

To test for reading variations, 10 charts were selected at random from our files. These charts were re-processed, by the same staff member, and the results compared to the results from the first readings. The results of this test are shown in Figure I-4 It can be seen that the average uncertainty in the data reading process is 2.4%.

Errors in Data Handling

These numbers (the raw data) are put into the computer system through a remote terminal. As the numbers are put into the system the computer checks for obvious errors—large numbers, negative numbers, etc. After the numbers from a maximum of 14 days' charts are entered, the computer is placed in a LIST mode. The numbers are printed out and the operator checks them against the original numbers. Errors in punching are then corrected in an EDIT mode. The final, corrected data is then stored in the computer. The possibility of significant error in this stage of the data manipulation is negligible, due to the two-fold error checking procedure.

Day (1977)	Location (Montana)	Total Daily Energy (KW-hr/m^2)				% Error
		First Reading	Second Reading	Error Between Readings	Average for Month	
Mar 1 (60)	Billings	5.156	4.947	.209	3.955	5.3
Jan 23 (23)	Bozeman	6.225	6.252	.027	3.258	0.8
Apr 2 (92)	Colstrip	3.723	3.679	.044	5.461	0.8
Apr 5 (95)	Great Falls	6.847	6.919	.072	5.547	1.3
Mar 13 (72)	Harlowton	2.621	2.857	.236	4.807	4.9
Feb 24 (55)	Lewistown	1.331	1.344	.013	3.979	0.3
May 8 (128)	Libby	5.507	5.369	.138	3.810	3.6
Mar 15 (74)	Missoula	4.816	4.952	.136	2.739	5.0
Mar 6 (65)	Polson	3.814	3.851	.037	3.100	1.2
Feb 19 (50)	West Yellowstone	6.465	6.491	.026	4.728	0.5

Average % error in test set: 2.4%

Average energy error in test set: .094 KW-hrs

Figure I-4: Data Reduction Reliability

Time (DST)	SIMM (Rel. Output) Energy	KIPP-ZONEN (Rel. Output) Energy	Calibration Factor	% Amplitude Deviation (3.100)	Energy Deviation
7	0.40	1.30	3.25	+4.8	.0624
8	1.12	3.55	3.17	+2.2	.0751
9	1.90	5.82	3.06	-1.3	.0756
10	2.55	8.00	3.14	+1.2	.096
11	3.12	9.65	3.093	-0.3	.029
12	3.52	10.88	3.091	-0.3	
1	3.68	11.40	3.098	-0.1	.033
2	3.64	11.32	3.110	+0.3	.033
3	3.45	10.65	3.087	-0.4	.043
4	3.01	9.28	3.083	-0.4	.037
5	2.40	7.5	3.125	+0.8	.06
6	1.63	5.3	3.25	+4.8	.254
7	0.78	2.8	3.52	+13.5	.442
		97.45 Total Energy			.8079 Total Deviation

$$\text{Daily Energy Error} = \frac{.8079}{97.45} \times 100 = 0.83\%$$

Figure I-3:
Calibration of SIMM Instruments
Results of a Calibration Run for an Entire Clear Day

REFERENCES

1. Blanco, P., "Solar Energy Availability and Instruments for Measurements," Solar Energy, Vol. 6, No. 3, 1962.

2. Daniels, F., Direct Use of the Sun's Energy, Yale University Press, 1964.

3. Haywood, H., "Simple Instruments for the Assessment of Daily Solar Radiation Intensity," U.N. Conference on New Sources of Energy, E35-89, Rome, 1961.

4. Majundar, N. C., and Kaushik, S. B., "Simple Instruments for Measurement of Direct Solar Radiation," Solar Energy, Vol. 8, No. 3, 1964.

5. Selcuk, K., and Yellott, J. I., "Measurement of Direct, Diffuse, and Total Solar Radiation with Silicon Photovoltaic Cells," Solar Energy, Vol. 6, No. 4, 1962.

6. Schoffer, P., Kuhn, P., and Sapsford, C. M., "Instrumentation for Solar Measurements," U.N. Conference on New Sources of Energy, E35-S92, Rome, 1961.

7. Bonner, M. G., and Sapsford, C. M., "Measurement of Solar Radiation by Silicon Solar Cell," Solar Energy, Vol. 10, No. 4, 1966.

8. Whillier, A., "Integrating Instrument for Measuring Solar Radiation," Solar Energy, Vol. 8, No. 4, 1964.

9. Bennett, I., "Monthly Maps of Mean Daily Insolation for the United States," Solar Energy, Vol. 9, No. 3, 1965.

10. Climatic Atlas of the United States, U.S. Dept. of Commerce, Washington, D.C.

11. ASHRAE Handbook of Fundamentals, Published by the Am. Soc. of Heat., Ref., and Air-Cond. Eng., 1974.

12. Liu, B. Y., and Jordan, R. C., "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation," Solar Energy, Vol. 4, No. 3, 1960.

13. Lof, G. O. G., Duffie, J. A., and Smith, C. O., "World Distribution of Solar Energy," Solar Energy, Vol. 10, No. 27, 1966.

14. Norris, D. J., "Correlation of Solar Radiation with Clouds," Solar Energy, Vol. 12, 1968.

15. Haywood, H., "The Computation of Solar Radiation Intensities," Solar Energy, Vol. 10, No. 51, 1966.

16. Hottel, H. C., and Woertz, B. B., "Performance of Flat-Plate Solar Heat Collectors," Trans. ASME, Vol. 64, No. 91, 1942.

17. Liu, B. Y. H., and Jordan, R. C., Low Temperature Engineering Applications of Solar Energy, ASHRAE, New York, 1967.

18. Duffie, J. A., and Beckman, W. A., Solar Energy Thermal Processes, John Wiley and Sons, 1974.

APPENDIX II:

DATA REDUCTION PROCEDURES

Introduction

The general flow chart for the data reduction is shown in Figure II-1.

The solar energy data consists of a continuous record of solar radiation versus time. At any instant of time the amplitude of the chart can be multiplied by the calibration factor of the instrument to yield the solar radiation, BTU/ft^2-hr (or kW/m^2). A sample set of curves for Helena is shown in Figure II-2.

One type of data that is useful is the total radiant energy falling on the transducer during the entire day, kW-hrs/m^2-day. This value can be determined from the area under the chart record. The approximate integration of the experimental curve is performed by constructing an approximate curve and then integrating that curve. The approximate curve consists of values averaged over an interval of 15 minutes. The integral of the approximate curve is then simply the sum of these incremental average values through the day.

The accuracy of this method of integration depends on the determination of the average values. The accuracy will vary from record to record, depending on the exact character of the radiation. A smooth curve, such as from a clear day, can be more accurately integrated than the irregular curve from a cloudy day. Because 60 or more increments are used to approximate each curve, errors in judgment will tend to cancel. A specific evaluation of the reliability of this procedure is given in a later section.

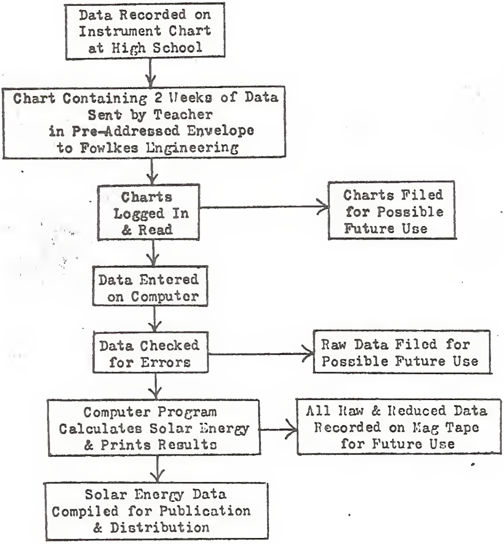
Computer Output

Figure II-3 depicts the data reduction process for one day. The basic solar insolation curve is shown in Figure 3a. The set of numbers representing the insolation curve is shown in Figure 3b. This set of numbers is checked for accuracy and then used to calculate the total and threshold energies, Figure 3c.

Results

Examples of the final daily radiation data for one station (Billings) for 12 days of operation is shown in Figure II-4 (Days are numbered consecutively, starting from January 1 as Day 1.) This data is averaged to obtain the values shown in the final compilation.

Figure II-1: Flow Chart for Solar Data


Data Recorded on Instrument Chart at High School
Chart Containing 2 Weeks of Data Sent by Teacher in Pre-Addressed Envelope to Fowlkes Engineering
Charts Logged In & Read
Charts Filed for Possible Future Use
Data Entered on Computer
Data Checked for Errors
Raw Data Filed for Possible Future Use
Computer Program Calculates Solar Energy & Prints Results
All Raw & Reduced Data Recorded on Mag Tape for Future Use
Solar Energy Data Compiled for Publication & Distribution

APPENDIX III:

NEW ACTIVITIES DURING FINAL QUARTER

Awards

The volunteer teachers were uniformly cooperative and enthusiastic during the first year's operation of SEMN. They were generally prompt in sending in the solar data and helped on some occasions to make minor adjustments in the recorder and transducer.

To recognize their contribution we made up "Certificates of Appreciation." The authority of these certificates was amplified with the signatures of John Orth and Governor Judge. A sample certificate is shown in Figure 5.

Manual Data Stations

We have been receiving data from the 30 manual stations since the beginning of the school year. We requested that the students or teachers take periodic solar intensity measurements using the manual instruments and enter them on a chart. These charts are sent to us monthly.

Our results have been variable and, as expected, depend on the dedication of the teachers and students. Most of the stations are returning daily noon readings as we requested. About 25-30% of the stations go far beyond our request and send us hourly data.

We are just beginning to compile this data. It will be necessary to do a careful statistical analysis of this data before we are prepared to include it with our data from the automatic recording stations.

I am convinced that much of the manual data will have significance when properly interpreted. The volunteers are certainly accruing a lot of educational value from their participation. The data from the manual stations is presented and discussed in the data section of this report.

Direct Data Reduction

Our present data reduction process (Appendices I and II) involves considerable handling of the data. The numbers are read from the chart, written down, entered into the computer, and checked. Each of these steps must be done for an average of over 1000 numbers each day. This is time consuming and the multiple steps expose the data to possible errors.

Initial work has begun on a curve reader. A prototype is shown in the photograph in Figure III-1. The purpose of this device is to streamline the data reduction process. The operation consists of the following steps:

(1) The chart paper containing the solar insolation curve sent by the high school is placed in the chart drive mechanism.

(2) The calibration factor for the particular recorder is set on the controls on the right hand part of the instrument.

(3) The zero of the chart is adjusted.

(4) The chart drive is activated and the pointer is manually positioned to follow the solar insolation curve.

The output of the curve reader is a time-varying electrical voltage which is an analog of the solar insolation. The time base of the analog signal is about one minute and represents about 12 hours real time. Once the instrument has been zeroed the entire two weeks of chart are read sequentially.

This data signal will be entered directly into a computer for integration, processing, and data storage. This system will reduce the amount of time now needed to read the curves manually. There will also be less opportunity for accidental error since the data signal will be entered directly instead of manually into the computer.

APPENDIX IV:
CONSULTANTS

Listed below are consultants who have contributed to the SIMM Program. A brief statement is included to describe their areas of expertise.

John Yellott

M.B.E.; O.S.J.; Registered Mechanical Engineer in Arizona, Maryland, and New Jersey; Fellow, A.S.M.E., A.S.H.R.A.E., A.A.A.S. Arizona Academy of Science.

Yellott Solar Energy Laboratory, 901 West El Caminito, Phoenix, Arizona 85021.

Mr. Yellott is a recognized expert in the areas of solar insolation measurement and solar energy utilization. His professional activities and publications would require several pages of description and are thus not included here. He has published original papers and holds patents in the area of solar insolation measurement using silicon cell transducers, the type of device used in the SIMM Program.

Mr. Yellott advised us during the early stages of the SIMM Program concerning instrument development. He has reviewed our calibration procedures, instrument design, and data processing. His advice has given us valuable assurance of the level of accuracy of our measurements. We feel fortunate that an internationally known solar expert is associated with the SIMM Program.

Bob Blair

B.S.E.E.

Department of Aeronautics, University of Washington, Seattle, Washington.

Mr. Blair is an electrical engineer. He has had broad experience in designing and building instrumentation systems for research and testing applications, including the Boeing Wind Tunnel, MHD and plasma research, shock tubes, holography, experimental mechanics, etc.

Mr. Blair helped to locate reliable and economical recording instruments for the SIMM Program. He continues to give us expert opinions on electronics questions regarding data reduction.

Phillip Mast

Ph.D.

Scientist, Naval Research Laboratory, Washington, D.C.

Dr. Mast has had over 20 years of research experience in the areas of materials, instrumentation, and computer applications. His experience ranges from original contributions to the theories of information to practical design and construction of computer hardware.

Dr. Hast has advised us concerning our data processing methods. Our goal is to incorporate and utilize state-of-the-art computer-assisted routines for processing the solar insolation data. By using these methods we hope to maximize the accuracy and minimize the cost of our data processing and storage.

Larry Thomas

Science and Mathematics Supervisor, Office of the Superintendent of Public Instruction, Helena, Montana 59601.

(Currently teaching in Helena.)

Mr. Thomas contributed a lot of time and ideas during the early stages of the SIEM Program. He helped to contact the high school volunteers and wrote many letters explaining who we were and what we planned to do. His advice and help in the communications area was invaluable.

Mr. Thomas consulted with us concerning the content of the "Handbook of Solar Energy Experiments." He read the first edition of this handbook and, as an expert in science teaching, gave his advice on changes in format and content of the handbook. His suggestions will be incorporated in future editions.

THE SPACING OF SOLAR MEASUREMENT STATIONS

Scientists, climatologists and mathemeticians have worked on the question of maximum allowable inter-station spacing. The basic goal is to distribute solar insolation recording stations close enough together so that values of solar insolation between the measuring stations can be estimated with a minimum or at least acceptably small error. This error is called "interpolation error".

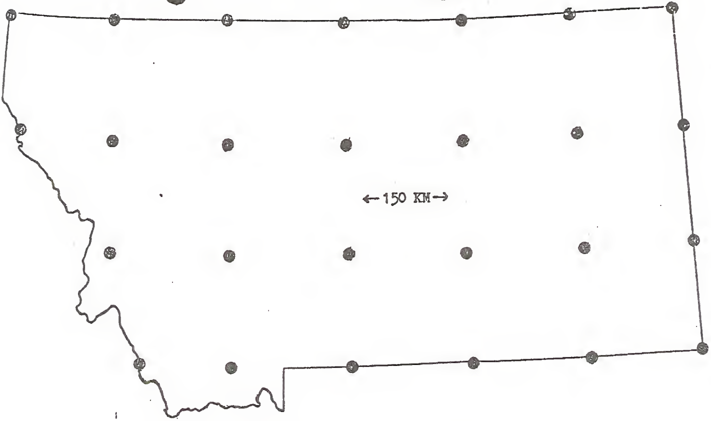
Some of the most complete work in this area is due to L. S. Gandin in The Planning of Meteorological Station Networks from the World Meteorological Organization of the United Nations. Other important material is available from D. O. E. contract EG-77-S-05-5362, Solar Radiation Data Sources, Applications, and Network Design. Statistical arguments and data from the latter are reproduced in detail in Appendix I.

To summarize, Gandin analyzed 48 stations and by a statistical argument concluded that for an optimal interpolation error of 0.11 the inter-station distance should be about 150 kilometers (91 miles). Figure 1a shows such an optimal grid covering the state of Montana. This grid contains a total of 26 stations. For comparison, Figure 1b shows the actual distribution of current SIMM measuring stations.

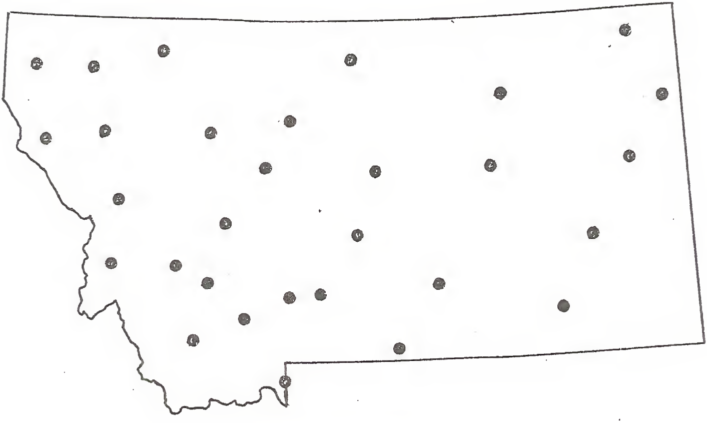
Conclusions

The current 30 station SIMM network is very similar to Gandin's "optimal" 26 station network. Since, at any given time there may be 1 to 3 SIMM stations off line due to operator error or machine malfunction, the current 30 station network is surprisingly close to Gandin's "optimal" network. Having a few extra stations allows the SIMM network to be tolerant of these errors and thereby has a built-in safety factor.

It appears that the current 30 station grid has a satisfactory density at present and should be maintained. Expansion of the grid would possibly be justified in some mountain-valley regions of the state where there may be significant local weather variations (Bozeman and Belgrade, for example). The current network has its highest density in the western and central region and this appears to be justified.



(a) "Theoretical Optimum"26 Station Grid



(b) Current 30 Station Grid

Figure 1: Comparison of Station Spacing

HOW MANY YEARS OF SOLAR DATA ARE NEEDED?

A basic concept of data collection is illustrated in the confidence curve shown in Figure 2. While literally thousands of pages in technical books and papers address this basic problem in a detailed coverage, this material is beyond the scope of this proposal. In this area we rely primarily on the expert judgment of scientists working in the field of solar radiation measurement rather than deriving the statistical arguments in detail.

For purposes of discussion it is helpful to consider the "confidence curve" in Figure 2. This curve illustrates that when no data is available the confidence level is "0". The first data points result in a large increase in confidence above the "0" level (the first year SIMM measurements). The later part of the curve tapers off illustrating the smaller increases in confidence as larger amounts (greater than 10 years) of data points are available.

There are two important reference points on this curve: at two years and ten years. The "two year" point represents the position of the second year SIMM program; that is, at the end of this current grant period. At the end of the two year milestone, the Department of Energy will consider including SIMM data in the national solar energy data bank. They feel that solar data over time spans less than two years is not significant.

The other milestone is the 10 year point. The NOAA National Weather Service requirement for publishing average solar energy data is 10 years of continuous solar measurements. Many meteorologists, incidentally, favor an 11 year minimum period for establishing average solar energy data. This preference results from the fact that the natural solar cycle is 11 years.

These reference points at 2 years and 10 years shed some light on the question of accepted time intervals for securing representative solar data and help to evaluate the status of our current measurment program. Additional information results by reviewing some actual SIMM data in the next section.

Annual Data Fluctuations

There exist natural variations in solar energy from year to year. These fluctuations are mainly due to fluctuations in local cloud cover. The weather pattern each year is to some extent unique. If data is taken for a long period to time, these yearly fluctuations can be distinguished from overall predominant weather patterns. It is these overall

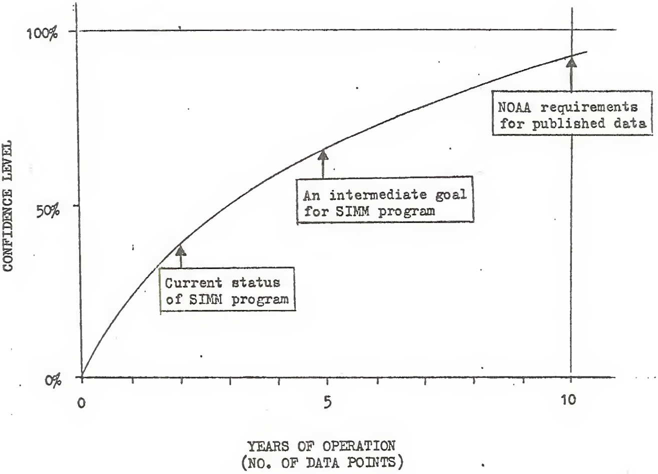


Figure 2: Confidence curve: for estimating the effect of measurement period on the confidence level for average solar insolation data

characteristics that are of practical use in solar energy utilization.

A solar heating system, for example, is expected to operate over the lifetime of the building which may be 20 to 50 years. The solar system must, therefore, be sized to correspond to some "average" radiation existing throughout this 20 to 50 year time period. A rule of thumb for solar design assumes that annual fluctuations in solar radiation will be normally contained in a band of ± 10-15% around the long time (10 years or greater) average.

Solar data fluctuations for the first four months of the years 1977 and 1978 for 14 stations has been plotted in Figure 3. These deviations are calculated by taking the difference in year 1977 and year 1978 data. The average daily total radiation for each month was used as the basis of the graph. A ± 10% and ± 15% band are also plotted on the graph to compare "expected" fluctuations to measured fluctuations.

Examination of the graph shows that there are more points outside the ± 10% band than there are within the band! This evidence indicates that at least one of the years is probably not a "typical" or "average" year. A second observation of Figure 3 is that if the ± 10% fluctuation band were displaced upward, more points would be contained in the band. This could indicate that (1) the solar energy during 1977 was unusually high or (2) the energy during 1978 was unusually low. Sufficient data is not available to scientifically or precisely answer this question at this time. Some reference can be made by looking at NOAA data.

Comparison with Great Falls and Glasgow NOAA data

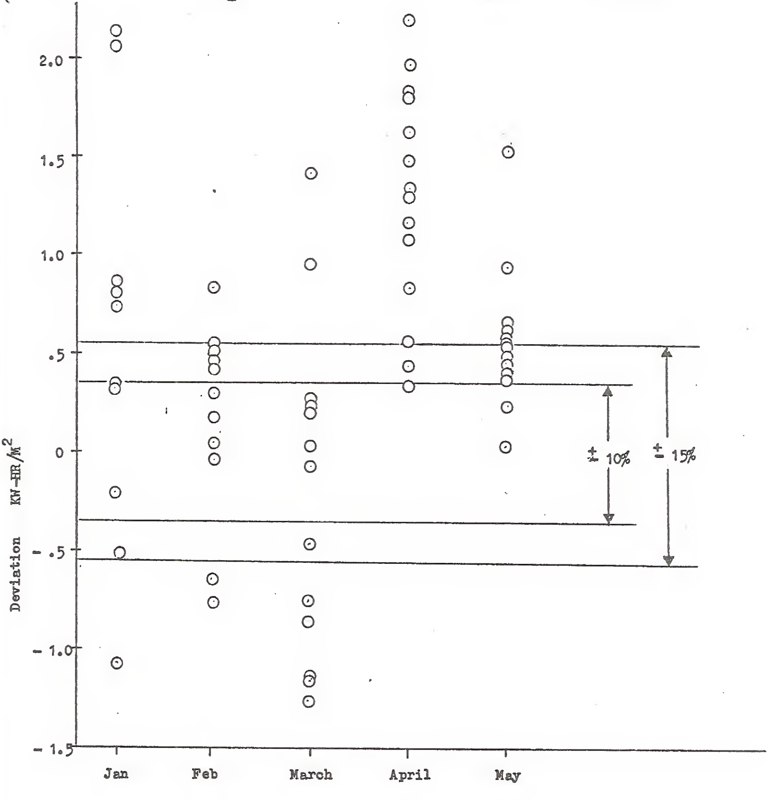
Long term averages (10 years) of solar energy falling on a horizontal surface are available from tables compiled by the National Weather Service of NOAA for (only) two locations in Montana: Great Falls and Glasgow. SIMM measurement stations were located at these two cities for the main purpose of providing a comparison of our current short-term to available long-term solar data. The NOAA average horizontal data was transformed, using accepted ASHRAE methods, to a 60^o surface for comparison to SIMM data.

Figure 4 shows a graph containing data from SIMM 1977 and SIMM 1978 along with long-term average NOAA data for Great Falls and Glasgow for the first six months of the year. There are several conclusions that can be drawn from this comparison:

① For 1977 and 1978 the solar energy available in Great Falls and Glasgow during the months of January, February and March averaged 40% lower than the 10 year average.

② The solar energy in 1978 for Great Falls and Glasgow was below average for the entire spring heating season.

1977-1978



Overall monthly average 3.6 KW-HR/M^2- Day

DEVIATION = Average Energy (1977) - Average Energy (1978)

Figure 3 : Yearly deviations in monthly average, daily solar energy for 20 stations

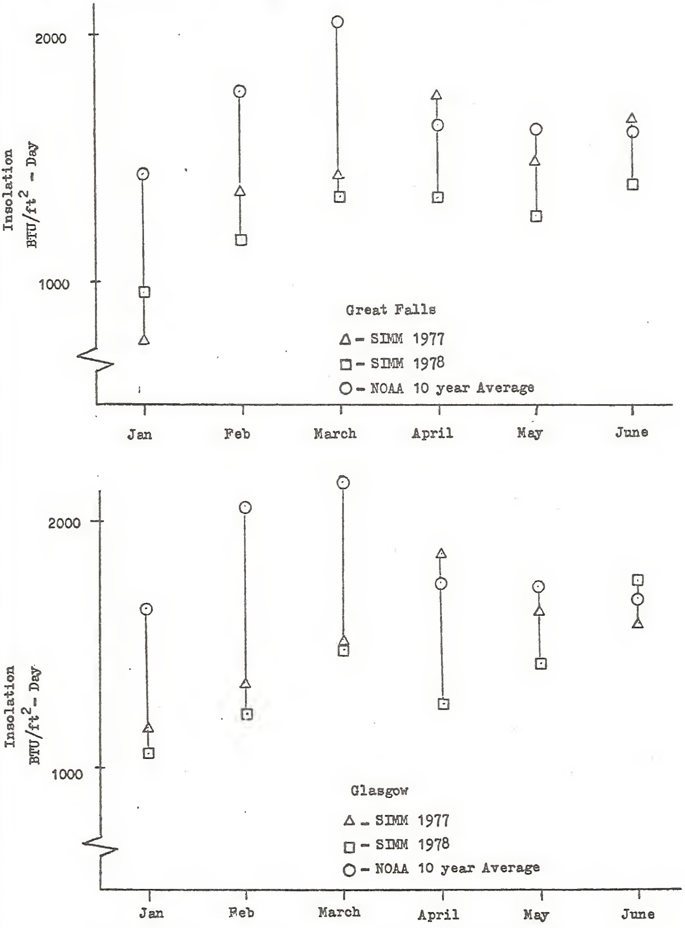


Figure 4: Comparison of long-term average data to SIMM data

③ The solar energy for 1977 in Glasgow and Great Falls during the months of April, May and June was "normal"; i.e. it fell within the ± 10% variance band when compared to long-term average values.

Conclusion

Solar data spanning a longer time period is needed to build a firm solar energy data base for Montana. The evidence indicates that both 1977 and 1978 have had an unusually small amount of solar energy during the crucial heating season in mid-winter and are not typical. Solar utilization systems designed to this short-term data would tend to be too large and hence less economically feasible.

The confidence curve in Figure 2 shows that about 10 years of data is needed to provide a 90% confidence level. This would bring the average solar energy values approximately within the ± 10% fluctuation band. After this 10 year point the pay-off in accumulating more data is small. For times less than 10 years each additional year of data yields a significant increase in confidence. It appears from the curve that a practical minimum time span for this measurement program would be 5 or 6 years.

On August 4, 1978 I was invited to Oregon State University to speak on our SIMM solar measurement program. The program was attended by meteorologists and scientists from 5 northwest states who are currently measuring solar energy resources and are planning expansions of these programs. During my talk I asked for opinions from this group on the length of time required to establish valid "solar energy averages". The general opinion was that 5 to 10 years of continuous measurement would be a practical goal.

SOLAR ENERGY DATA FROM SIMM PROGRAM

Introduction

This section describes the data handling in the SIMM program. The present status of the data for 1978 is indicated by the bar graph in Figure 5 .

Data Reduction

The general flow chart for the data reduction is shown in Figure 6 .

The solar energy data consists of a continuous record of solar radiation versus time. At any instant of time the amplitude of the chart can be multiplied by the calibration factor of the instrument to yield the solar radiation, Btu/ft^2- hr (or kw/m^2). A sample set of curves for Helena is shown in Figure 7 . Figure 8 shows curves from four different cities taken on the same day.

One type of data that is useful is the total radiant energy falling on the transducer during the entire day, kW-hrs/m^2 - day. This value can be determined from the area under the chart record.

Reading Chart Records

The solar energy data is recorded and sent to our office in the form of strip chart records. Last year we read numbers from these charts and then enetered them, by hand, into a computer system. Although this method worked quite well, a lot of time was required to process the data. The associated computer rental time was also expensive.

A study of this problem indicated that methods should be developed for entering the chart data directly into the computer using a curve reader. Devices for inputting graphical data have been available for several years but their cost has been prohibitive for a project of our scale and budget. Cost reductions and developments during the past few months in the computer field have placed usable systems within reach.

We now have in our office a 32 K, 8 bit digital computer system with dual magnetic disc storage. This system has a keyboard and video terminal for communication with the computer. A special feature is a graphic input tablet which is interfaced directly to the computer.

STATUS OF 1978 SOLAR DATA BANK

August 14, 1978

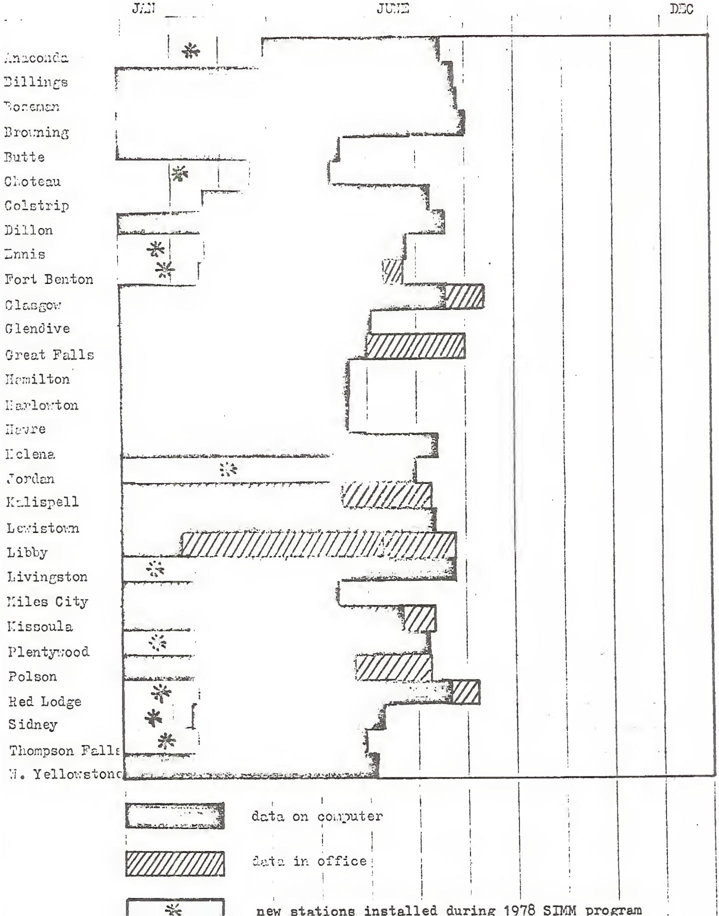
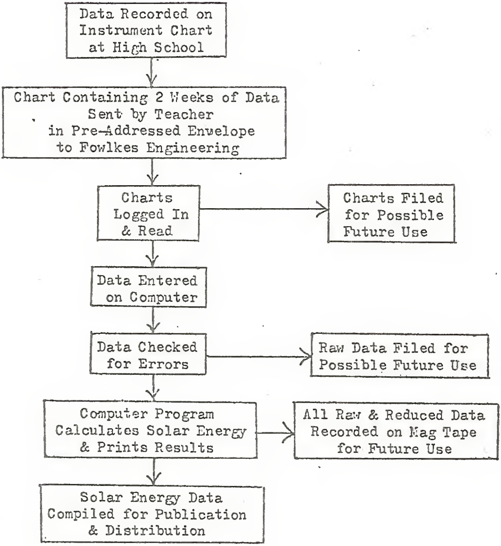


Figure 6: Flow Chart for Solar Data


Data Recorded on Instrument Chart at High School
Chart Containing 2 Weeks of Data Sent by Teacher in Pre-Addressed Envelope to Fowlkes Engineering
Charts Logged In & Read
Charts Filed for Possible Future Use
Data Entered on Computer
Data Checked for Errors
Raw Data Filed for Possible Future Use
Computer Program Calculates Solar Energy & Prints Results
All Raw & Reduced Data Recorded on Mag Tape for Future Use
Solar Energy Data Compiled for Publication & Distribution

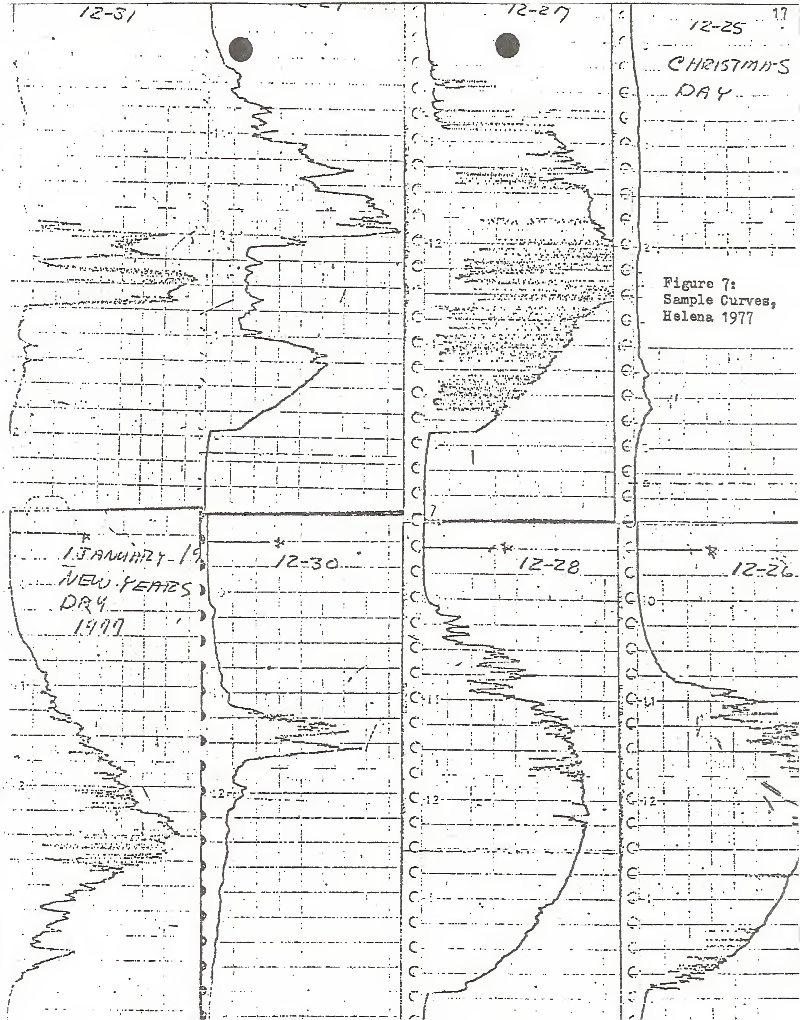


Figure 7: Sample Curves, Helena 1977

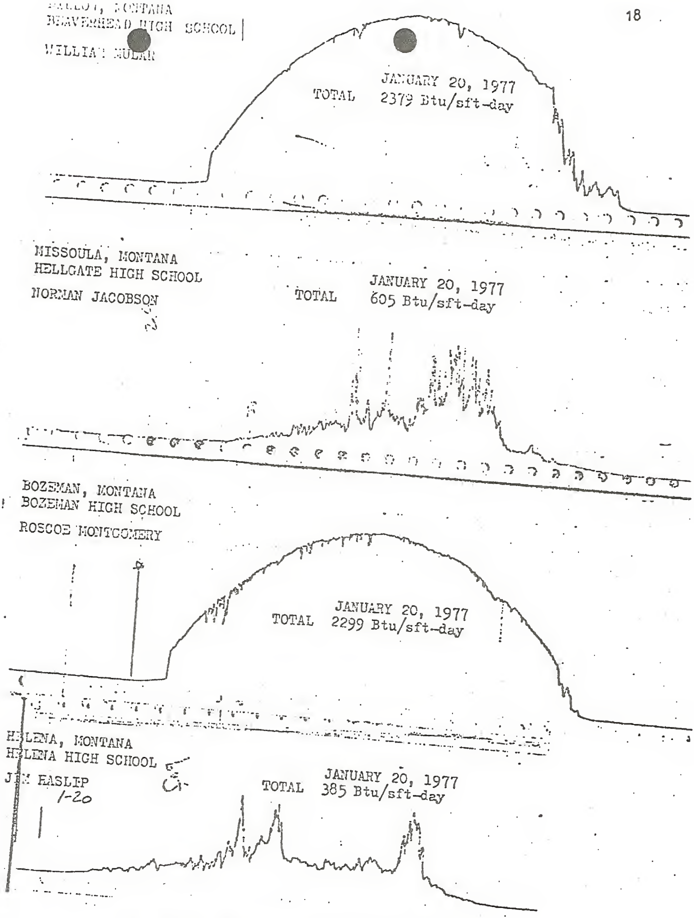


Figure 8: Solar Energy Recordings for Four Different Montana Cities, Taken on the Same Day, January 10, 1977

The input tablet consists of a flat platen about 12 inches square and a cursor which looks like a pen. When the pen is touched to the platen, the system outputs the x-y coordinates of that point on the platen directly into the computer in digital form. Thus when a curve is continuously traced on the platen, a series of x-y coordinates which represents the curve is simultaneously input to the computer.

If a solar energy chart record is placed on the platen, the graphical information can be directly entered into the computer by simply tracing the curve on the chart record. This device eliminates much of the "hand work" and promises to improve accuracy as well as economy. A photograph of the system is shown in Figure 9.

New Data Reduction Process

A schematic flow chart of the data reduction and storage using this system is shown in Figure 10. The main features of this process are the use of the graphics input tablet to enter the solar energy chart records. The reduced data is stored on magnetic floppy discs in the form of time-of-day averages of solar intensity. The file structure of the data storage is outlined in Figure 11.

Once the solar data is in computer-readable form on the magnetic disc it can be easily and efficiently processed and ouput in any desired format. A primary output is Tables of Average Insolation in the format used during 1977 in the SIMM program. Direct computer simulations of solar systems would also have been run using this system.

Threshold Radiation

In addition to total radiation data, we are also calculating the radiation above a series of thresholds. The reason for calculating threshold data derives from the operating characteristics of nearly all solar collectors. A solar collector is normally operating only during periods of relatively high solar intensity. This is due to the losses inherent in any collector. In early morning or evening hours or during other periods of low radiation, the collector will lose more heat than it will gain. The radiation falling on the collector must be of an intensity great enough to raise the collector surface temperature ABOVE the temperature of the storage reservoir.

For example, if the storage reservoir has a temperature of 125° F and the ambient air is 25° and if the collector is double-glazed , the heat loss through the glazing will be about 0.68 Btu/ft^2 – hr – ° F. or about 68 Btu/hr-ft^2 .

Assume that other conduction losses, when added to this, result in a

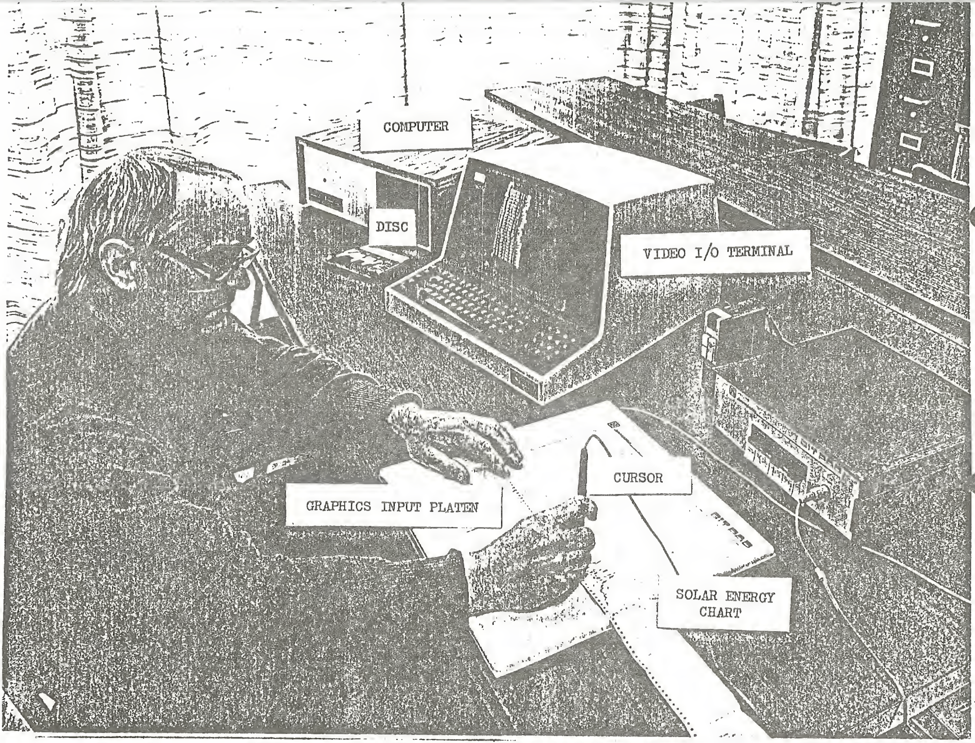
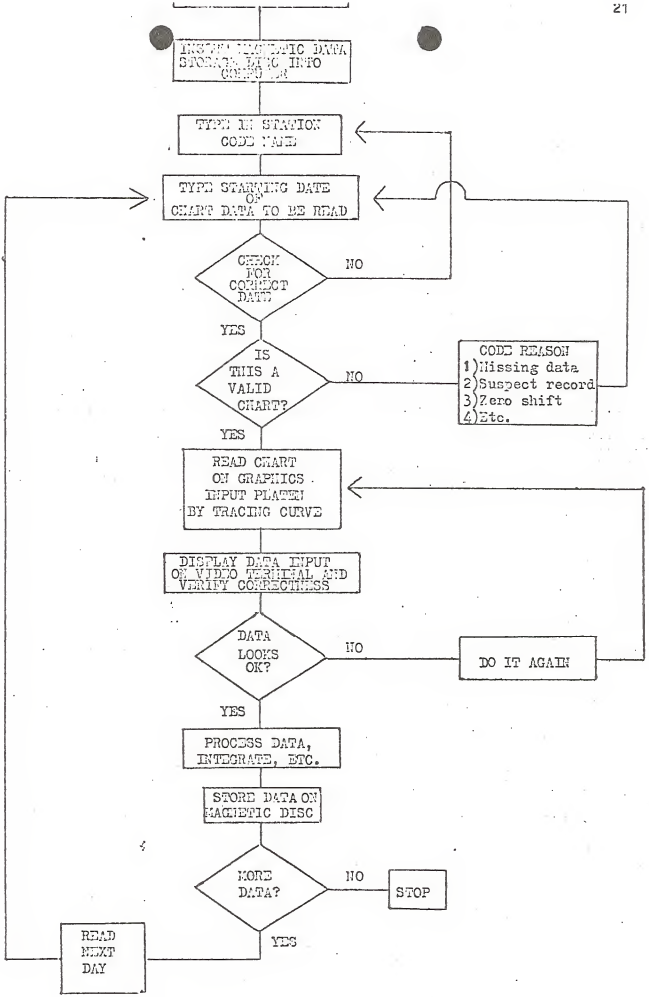


Figure 9: Photo of Data Reduction System


INSERT MAGNETIC DATA STORAGE DISC INTO COMPUTER
TYPE IN STATION CODE NAME
TYPE STARTING DATE OF CHART DATA TO BE READ
CHECK FOR CORRECT DATE
NO
YES
IS THIS A VALID CHART?
NO
CODE REASON
1)Missing data
2)Suspect record
3)Zero shift
4)Etc.
YES
READ CHART ON GRAPHICS INPUT PLATEN BY TRACING CURVE
DISPLAY DATA INPUT ON VIDEO TERMINAL AND VERIFY CORRECTNESS
DATA LOOKS OK?
NO
DO IT AGAIN
YES
PROCESS DATA, INTEGRATE, ETC.
STORE DATA ON MAGNETIC DISC
MORE DATA?
NO
STOP
YES
READ NEXT DAY

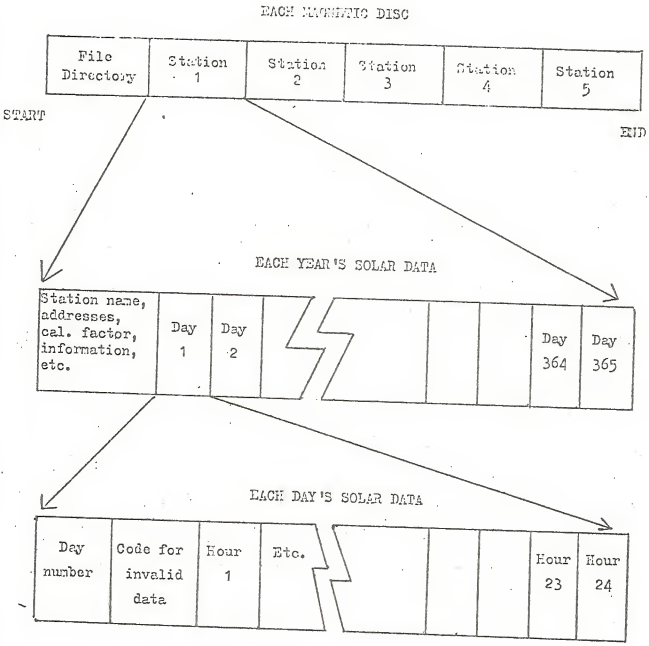


Figure 11: File structure for storing solar insolation data

total loss of 90 $Btu/hr-ft^2$. Thus, if tho radiant intensity is less than this amount, the collector will operate at a net LOSS.

A series of thresholds from 0.1 kW/m^2 to 1.2 kW/m^2, spaced 0.1 kW/m^2, is used. Given the operating threshold of a particular collector, it is possible to interpolate the data to determine the actual energy available.

Data Tables

To demonstrate some of the data that is currently on record we have printed the data tables in Appendix II. The format of the tables is similar to the format used for the tables presented in last year's final report. The day numbers refer to the day of the year with January 1 being day 1, etc. Individual daily totals as well as a breakdown of the intensity spectrum are given.

Fault Codes

As we enter the data we also record a "fault code" for the data. If the data is missing or suspect due to instrument or operator malfunction we record that data on the disc by entering the appropriate fault code number. This will allow us to scan through the data at year's end and compile and categorize the frequency and types of data problems or losses.

Some small faults in the data are recoverable and we have routines built into the computer program to adjust these curves so that we can still use them. Any data that we have adjusted is noted with an appropriate fault code so that we can separate it from normal valid data. In the tables recovered data is noted by parentheses around the total energy value for that day.

Accuracy Checks

We are currently running accuracy checks by repeating about 300 data days of chart records. The comparison of these records will give us a good idea of our repeatability. We plan to do periodic random checking of the data entry process to maintain a running record of the accuracy of our data reduction process. Current test results show that our average accuracy is better than 2.5%.

Conclusion

It is significant to note that our data reduction system closely parallels an elaborate system developed under a D. O. E. contract for reclaiming solar energy chart data in the United States. We can thus feel confident that we are technically "up to speed" in this area of reducing solar energy charts. An economic comparison in another section of this proposal shows that we are doing this data reduction job for about 20% of D. O. E. costs.

TECHNICAL DISCUSSION OF SOLAR INSTRUMENTATION AND ACCURACY

Commercial Instruments

Reviews of currently used solarimeters and pyranometers are given by Blanco (1), Daniels (2), Haywood (3), and Majumdar (4). Instruments based on thermo-electric measurement, calorimetric measurement, and photovoltaic measurement are available. The best known and most widely used instruments are the Eppley and Kipp pyranometers. The Eppley, which is manufactured in the United States and commonly used here, consists of a blackened metallic receiver 3 cm in diameter surrounded by a white or silver outer ring. A copper- constantan thermocouple is attached to the blackened receiver with the cold junction attached to the reflective outer ring. The temperature difference between the black body and the reflective body gives a measure of the radiation. The reflective ring remains at nearly ambient temperature. The daily output of the thermocouple is measured by a recording pyranometer. This curve is then integrated to give total daily radiation.

The receiving surface is normally placed horizontally and covered by a hemispherical, transparent glass or plastic cover. The direct radiation as well as the diffuse radiation fall onto the surface and are recorded. Properly calibrated, the Eppley and Kipp pyranometers have an accuracy of ± 5%.

Photovoltaic Instruments

Experiments have been performed to test the applicability of silicone photovoltaic cells for solar radiation measurements by Yellott (5), Schoffer, et. al. (6), Banner, et. al. (7), and Whillier (8). A commercial instrument, the Sol-A-Meter, is currently manufactured by Matrix, Inc., of Phoenix, under a license from John Yellott.

The silicon cell consists of a p-n junction of ultra-pure silicon. Photons striking the cell cause electrons to be displaced, which is a current. Under proper loading conditions, the current flow is directly proportional to the incident radiation. This behavior makes the silicon cell a candidate for solar measurement.

The advantages of the silicon transducer are its relatively high electrical output and its long-term stability and reliability. Its disadvantages include a slight temperature dependence and a spectral sensitivity which departs from black body behavior. Extensive experiments are reported in the references above which compared standard Eppley and Kipp pyranometers with silicon cell pyranometers (5,7,8). These experiments show that the silicon instruments can produce results within ± 5%. Most of the inaccuracy occurs when the sun is at low angles. The variation of calibration with optical path length is related to the spectral response of the cell. This effect may be seen in the calibration data for the SIMM instruments used in this program.

Instruments for the SIMM Program

Instruments based on the silicon cell transducer were chosen for use in the SIMM program for two reasons: (1) the overall cost of the instruments was minimized and (2) the characteristics of the transducer have been well documented. That is, the silicon cell measurements are related to the standard radiation instruments.

This second factor is very important. There are a large number of photovoltaic and photoresistive transducers available at the present time. Any of these devices, when connected to the proper circuit or meter, will give some change in output with variations in "light" intensity. The common Cd-S photographic light meter is an example. Due to linearity problems and spectral response, this system would not be useful for energy measurements.

The immediate purpose of the SIMM program is to make measurements which will accelerate the utilization of solar energy. It is therefore important that there be a direct relationship of the measurements made to the measurements needed for solar design. Since this relationship has been documented in the literature (5,6,7,8), no additional development or research programs are needed to establish the "meaning" of the measurements.

Prof. John Yellott has U.S. patents covering some aspects of solar measuring instruments using silicon cells. I have described the SIMM program and the instruments to him. He has assured me that the SIMM instruments (1) would not infringe on his patents and (2) would be quite accurate and easy to calibrate.

Description of the SIMM Instrument Package

The instrument package distributed to the high school measuring stations consists of two solar radiation measuring units, the SIMM-1 and the SIMM-1R. Photographs of the instruments are shown in Figure 12.

SIMM-1 is a hand-held instrument. It consists of a silicon cell mounted on a tiltable plate. The plate is hinged to a small instrumentation box which contains the indicating meter. The instrument is self-powered and needs no batteries. It is used in this program as a back-up instrument and as an educational tool.

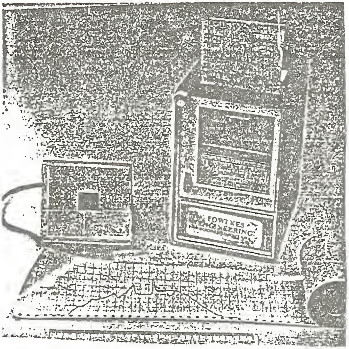
The SIMM-1R instrument incorporates a strip chart recorder so that a continuous record of solar energy can be obtained. The recorder drive is powered by 100 vac. The transducer is separate from the recorder and consists of a silicon cell mounted on an angled plate. This assembly is designed for attachment to an exterior wall or roof. The recorder is located inside the building on a convenient shelf or cabinet.

Transducer Orientation of SIMM-1R

The silicon cell in the SIMM-1R transducer is mounted facing south and at an angle of 60 degrees from the horizontal. This orientation is chosen because it is nearly the optimum winter collection angle for Montana. The data taken at this angle can accurately be trasnformed to other similar angles. Weather bureau data records radiation on a horizontal surface. Transforming this data to practical collector angles produces error. (In Montana in the winter the altitude of the sun is about 20 degrees.) It is the philosophy of this program to make measurements which will implement the utilization of solar energy. This goal is achieved by taking the data at orientation matching the ultimate device.

Errors in Data Reduction

The new direct computer data reduction has improved the speed and accuracy of this process. We have tested the reproducability of the data reduction procedure by conducting a test in which we took a sample consisting of 300 data-days from Billings and Bozeman. This 300 day sample was read two times. The average monthly insolation was calculated separately for each run and then compared. The variation was a minimum of less than 1% and a maximum of 5%. The average variation was less than 2.5%.

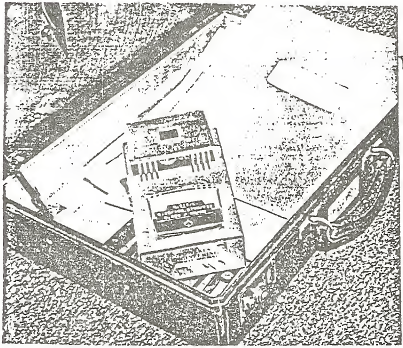


Solar Energy Transducer, mounted on outside of building

Chart Recorder, located inside building

Chart Record containing data

Solar Energy Recording System, SIMM-1R
20 units currently operating across Montana.



Manual Solar Energy Instrument

"Handbook of Solar Energy Experiments"

Manual Solar Energy System, SIMM-1
50 units currently located across Montana.

* APPENDIX I

OPTIMAL INTER-STATION SPACING

The concept of forecasting time-series events is not new. Almost any variable which is observable at discrete time points may be molded into a mathematical model which may closely resemble local-time-segment observations. Once a valid model for a time series process has been established, forecasting analysis may render useful service in predicting performance or examining system modifications.

Of particular interest are stationary processes. That is, those processess which have values fluctuating about a constant mean. These processes are unaffected by a shift of the time origin, and may be modeled by taking observations at equal time periods. Within a single given process, a correlation of these time observations (autocorrelation may appropriately be used) may allow construction of a predictive model for observations at specific time increments or time lags. As stated by Montgomery and Johnson:

> For a stationary time series the mean is just
>
> $$E(x_t) = E(m + \sum_{j=0}^{\infty} \psi_j \ \varepsilon_{t-j}) = m + E\sum_{j=0}^{\infty} \psi_j \ \varepsilon_{t-j}$$
>
> and since the sum $\Sigma_{j=0}^{\infty}= \psi_j$ converges, we take expectation of $\Sigma_{j=0}^{\infty} \psi_j \varepsilon_{t-j}$ term by term, yielding $\Sigma_{j=0}^{\infty} \psi_j E(\varepsilon_{t-j})=0$. Thus the mean of the stationary series is
>
> $$E(x_t)=m$$
>
> The variance of the time series process is
>
> $$\begin{aligned}\gamma_0 &= V(x_t)=E[x_t - E(x_t)]^2\\ &= E[\sum_{j=0}^{\infty}\psi_j\varepsilon_{t-j}]^2\\ &= E[\sum_{j=0}^{\infty}\psi_j^2\varepsilon_{t-j}^2 + \text{cross products}]\end{aligned}$$
>
> and since the $\{\varepsilon_i\}$ are independent, the cross products have zero expectation, yielding
>
> $$\gamma_0=\sigma_{\varepsilon}^2 \sum_{j=0}^{\infty} \psi_j^2$$
>
> The variance exists only if $\Sigma_{j=0}^{\infty}=\psi_j^2$ converges.
>
> The covariance between x_t and another observation separated by k units of time x_{t+k} is called "autocovariance" at lag k, and is defined as
>
> $$\gamma_k=Cov(x_t, \ x_{t+k})=E[x_t-E(x_t)][x_{t+k}-E(x_{t+k})]$$

---

* From Solar Radiation Data Sources, Applications and Network Design, ERDA Contract 77-S-05-5362, Carter, et.al., 1978.

Thus the autocovariance is just like the covariance of two random variables; the prefix "auto" merely implies that we are referring to the covariance of any two observations in a time series that are k time periods apart. It is not difficult to show that the autocovariance at lag k is

$$\gamma_k = \sigma_\varepsilon^2 \sum_{j=0} \psi_j \psi_{j+k}$$

Within the framework of the Box-Jenkins methodology, time series models are characterized by their autocorrelation functions. The correlation between two random variables, say W and Z, is defined as

$$\mu_{wz} = \frac{\mathrm{Cov}(W,Z)}{\sqrt{V(W)\ V(Z)}}$$

Thus the autocorrelation at lag k refers to the correlation between any two observations in a time series that are k periods apart. That is,

$$\mu_k = \frac{\mathrm{Cov}(x_t, x_{t+k})}{\sqrt{V(x_t) \cdot V(x_{t+k})}} = \frac{\gamma_0}{\gamma_1}$$

is the autocorrelation at lag k. A graphical display of μ_k versus lag k is called the autocorrelation function $\{\mu\}$ of the process. Notice that the autocorrelation function is dimensionless and that $-1<\mu_k<1$. Futhermore, $\mu_k = \mu_{-k}$; that is, the autocorrelation function is symmetric, so that it is necessary to consider only positive lags. In general, when observations k lags apart are close together in value, we would find μ_k close to 1.0. When a large observation at time t is followed by a small observation at time t+k, we would find μ_k close to -1.0. If there is little relationship between observations k lags apart, we would find μ_k approximately zero".[1]

The application of forecasting technique to seasonal actinometric data by L. S. Gandin is of particular interest in that Gandin computes autocorrelation coefficients of observational data for zero time lags. These correlation coefficients are then graphically displayed as a function of inter-station distance.[2] From his formula for interpolation error for square-grid-station networks, he then computes interpolation error:[3]

$$\varepsilon = 1 - \frac{4\mu^2 \, (\rho/\sqrt{2})}{1 + 2\mu\rho + \mu\rho\sqrt{2} + n}$$

where:

n = the measure of observational error (the ratio of the mean square error to the variance of interpolated magnitudes here taken to be .25).

μ = the correlation coefficient of the station under scrutiny

ρ = the station-to-station distance or the area attributed to a single station within a square-grid network.

After errors have been computed for each station, they are plotted as a function of distance. Optimal inter-station distance may then be determined by calculating optimum interpolation error for the number of states within the data of interest,

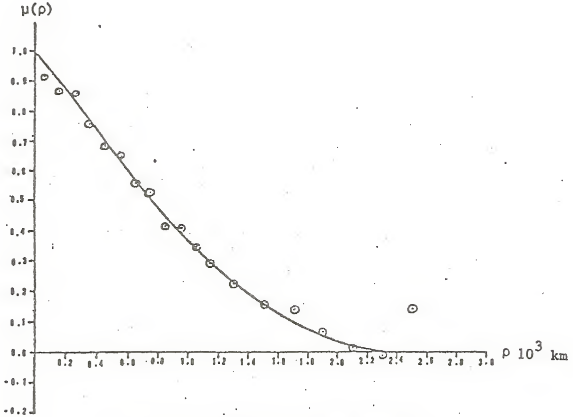
$$\varepsilon^* = \frac{1}{n^2} = .25 \text{ for } n = 2,$$

and reading the optimal inter-station distance from the graph.[4]

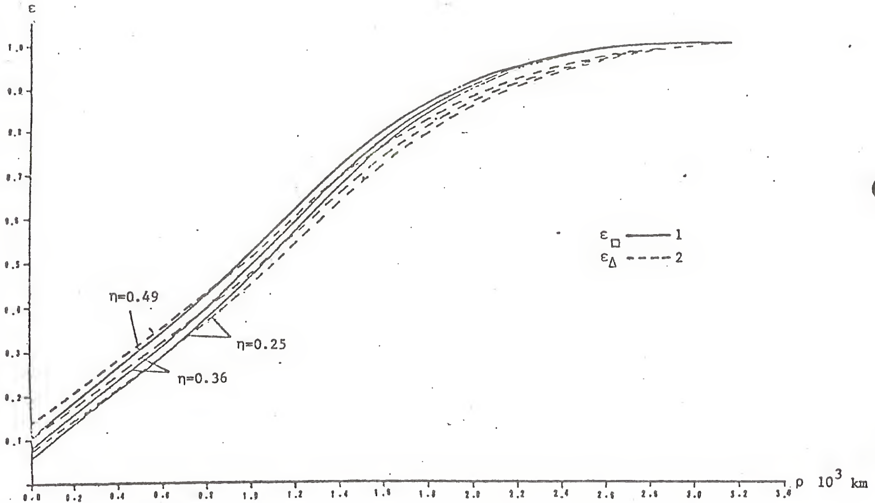
This analysis was duplicated for four actinometric stations in South Carolina. For 1970 seasonal data, individual months were examined ie. January, April and July. Analysis has yielded curves which are not displayed, [illegible] For an optimal interpolation error of .25, the inter-station distance can be determined from Graph 2 to be approximately 75 kilometers.

Examination of Graphs 1 and 2 display Gandin's work in analyzing 48 stations within the Soviet Union. For an optimal interpolation error of .111, Gandin determines the inter-station distance to be 150 kilometers.

In comparison of a 4-station network with a 48-station network, it must be said that only a demonstration of Gandin's technique has been



Graph 1 - Autocorrelation function of monthly totals of global radiation Summer.



Graph 2 - The relationship of measure of optimum interpolation error in the center of square, $\varepsilon_\square$ and of triangle, ε_Δ, to ρ for different values of the measure of observation error η. Stations are supposed to be situated at the apices of the indicated squares and triangles.

attempted. Moreover, the least-square fit could not be presumed to overlay Gandin's curves exactly since the aerological contours of the regions are different and since the period of records are not the same. Also an optimal interpolation error value of .111 should be used to coincide with Gandin's network, if a true comparison were to be effective.

In conclusion, to further investigate this technique, data from a larger number of stations should be examined. This would create more data points for curve-fitting and would result in more meaningful results.

The purpose of explaining this procedure is to provide a first order approach for evaluating the value of solar radiation measurements interpolated to intermediate points. This will, in turn, help to evaluate or justify the need for additional data in the network area. Additional studies of this and other methods of determining optimum spacing of stations are in progress, and the reader is advised to seek the latest methods for determining the quality of interpolated data between stations.

---

[1] Montgomery, D. C. and L. A. Johnson, Forecasting and Time Series Analysis (1976), New York: McGraw-Hill Book Co., p. 190.

[2] Gandin, L. S., United Nations, Estimation of Maximum Permissable Distance Between Actinometric Stations, CCl - v/Doc. 30, Appendix B, World Meteorological Organization, p. 4.

[3] Gandin, L. S., United Nations, The Planning of Meteorological Station Networks, WMO - No. 265. TP. 149, World Meteorological Organization (1970), p. 13.

[4] Gandin, loc cit., p. 2.

FINAL REPORT

TO

DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
ALTERNATIVE RENEWABLE ENERGY SOURCES

FOR

SOLAR INSOLATION MEASUREMENT, MONTANA

GRANT RAE 084-FWLKS-772

1978-79

from

Fowlkes Engineering
31 Gardner Park Drive
Bozeman, MT 59715

Introduction

The work outlined in the original proposal has been accomplished. The scope of the work was increased to include (a) reduction of solar data collected between grant periods and (b) preparation and reproduction of a summary data document. This was done with no increase in the alloted budget amount.

A brief overview of the scope of the national solar radiation data base is given in Figures 1 and 2. Figure 1 shows stations for which reliable, global radiation is archived at the National Climatic Center. Figure 2 shows current stations not in the NOAA network; this map indicates 20 stations from the SIMM network.

Figure 2 shows that Montana, Oregon and California are clearly in the lead in terms of solar network density. Montana's leadership position is due to the support of SIMM by the Alternative Renewable Energy Sources Program.

The following section lists milestones accomplished during the grant year for RAE 084-FWLKS-772. These exhibits are intended to document the work done on this grant.

Milestones

Exhibit I: Montana Solar Data Manual

The Montana Solar Data Manual was compiled in late spring and early summer during an extension on the grant. This 170 page Manual summarized solar data collected during the past two grant years and includes auxiliary information useful to the solar designer.

A total of 350 copies of this Manual were reproduced: 250 copies were sent to DNR, 50 copies were distributed to participating high schools

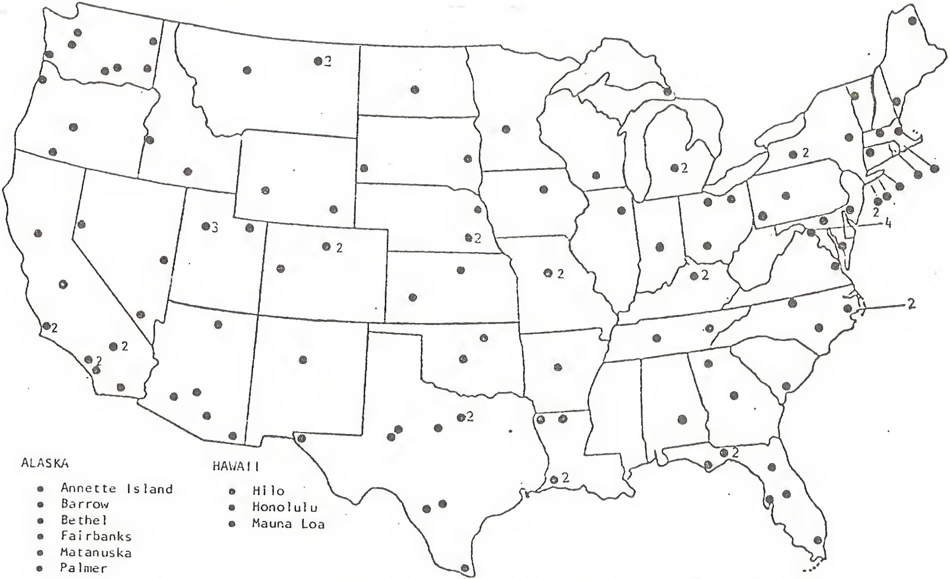
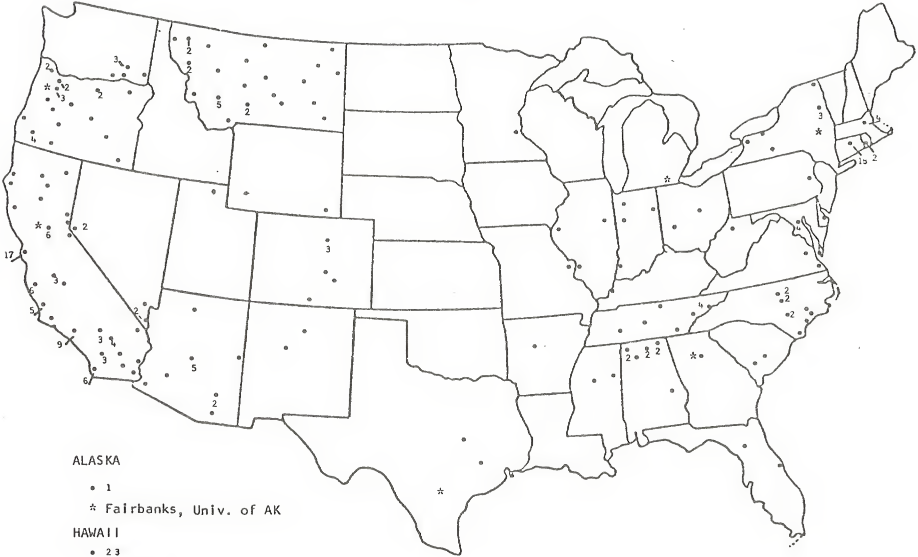


FIGURE 1 - SOLAR RADIATION STATIONS WITH DATA ARCHIVED AT THE NATIONAL CLIMATIC CENTER, ASHEVILLE, NORTH CAROLINA. NUMBERS INDICATE MORE THAN ONE STATION IN AREA.



ALASKA

• 1

* Fairbanks, Univ. of AK

HAWAII

• 23

* Univ. of HI

FIGURE 2 - SOLAR RADIATION STATIONS NOT IN THE BASIC NATIONAL WEATHER SERVICE, NOAA, NETWORK. ASTERISKS DENOTE DOE RESEARCH AND TRAINING SITES. NUMBERS INDICATE MORE THAN ONE STATION IN THE AREA.

and 40 copies were distributed primarily to professionals and government agencies outside of Montana.

(Note: Copies of the Manual are not attached to this report as they are available at DNR.)

Exhibit II: The Montana Solar Radiation Measurement Network (attached)

This paper was presented at Solar '79 Northwest in Seattle on August 11. This meeting was jointly sponsored by the U.S. Department of Energy, Bonneville Power Administration, Washington State Energy Office and Oregon Department of Energy. Over 100 technical papers were presented for the (estimated) 1000 people attending the conference.

The paper describes the SIMM program operation, instrumentation and data output.

Exhibit III: Handbook of Solar Energy Experiments (attached)

This Handbook was prepared as an integral part of the SIMM program for distribution to the participating high schools. The earlier version of this Handbook has been considerably enlarged this year by including several new solar energy experiments. The new experiments focus on solar utilization. They include instructions for building and testing simple active, passive and concentrating collectors. Most experiments may be carried out as simple demonstrations or as more detailed tests. The solar basics are emphasized to encourage the students to grasp the concepts of solar utilization. The 30 schools having insolation recorders, as well as the schools having manual instruments, receive the Handbook.

Exhibit IV: "Solar Radiation Observation Stations, Updated to 1979" (attached)

This document was prepared by the Johnson Environmental and Energy Center of the University of Alabama. The purpose of this effort was to catalog stations within the U. S. where solar insolation was being measured. The maps in Figures 1 and 2 were taken from this document and all thirty of the stations in the SIMM network are listed.

Exhibit V: NOAA Calibration (attached)

The silicon cell transducer used in the SIMM program was calibrated by Edwin Flowers of NOAA for approximately two weeks against the NOAA reference standard. This data will allow us to more accurately establish the accuracy of our data in the future. As a parallel effort, the Kipp pyranometer which had been used as our secondary standard was recently re-calibrated by NOAA. The calibration of the Kipp had not changed significantly. These efforts in conjunction with our clear-day procedure insure the integrity of our data.

Conclusion

In addition to these major milestones there has been a gradual increase in awareness of the SIMM program in people outside Montana. I have made two presentations in Washington and Oregon to regional groups involved in radiation measurement. We have also answered numerous requests for information from individuals within DOE, SERI, State Energy Offices and Universities concerning the SIMM program.

Measurements and data compilation are currently being continued at the 30 stations. During the summer a technician visited all stations, checked the instruments and made necessary repairs. During the coming year more work will be done on calibration and ideas for improving the Data Manual will be solicited.

Budget

Table I outlines the expenditures as of March 31, 1979. At this point there was a balance of $3,952.48 and the goals of the proposal had been accomplished with the exception of the data handbook. At this time a request was made to expand the scope of the proposal, using these funds to pay for the extra work. This request was approved by DNRC.

There were two main tasks in the expansion. The first task was to reduce strip chart data which Fowlkes Engineering had collected during late 1977. This data had never been reduced because it was accumulated during a gap in the funding between the first and second year of the grant.

The second goal was to expand the proposed 50 copies of the 1978 data document into 350 copies of a much broader document, the Montana Solar Data Manual, containing both 1977 and 1978 data along with auxiliary design information.

Table II itemizes the use of the $3952.48 for accomplishing these expansions. It will be noted that the expansion cost exceeded the money available by $663.77, due primarily to a large amount of computer time to output the Data Manual. This overrun will be absorbed by Fowlkes Engineering.

Final Budget Request

Enclosed is a grant request for $3547.50. This is the amount remaining in the grant after the previous quarterly advances. The final budget distribution was much the same as the original. The largest transfer was $673.98 from maintenance into Data Manual reproduction: the remaining transfers were typically around $200.

THE MONTANA SOLAR RADIATION MEASURING NETWORK

Charlese W. Fowlkes
Fowlkes Engineering
31 Gardner Park Drive
Bozeman, MT 59715

ABSTRACT

This paper describes the operation and results of a current state-supported program, Solar Insolation Measurement, Montana (SIMM). The goal of this program is to measure and document the solar insolation available at 30 locations within the state of Montana. This solar insolation data base will be useful to designers of solar energy conversion systems. The existence of this data base is intended to stimulate the utilization of solar energy in Montana. To date, over 20,000 solar insolation data-days have been collected. A summary of most of this data is available to the public in the recently published Montana Solar Data Manual, Fig. 1 (Fowlkes, 1979).

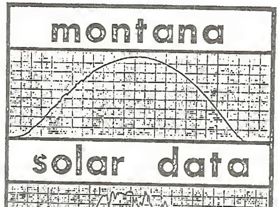
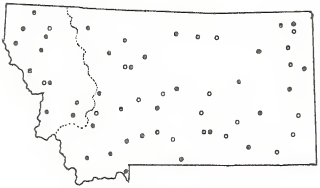


Fig. 1. Cover of Montana Solar Data Manual, illustrating solar insolation records (including eclipse on Feb. 26, 1979).

INTRODUCTION

Early in 1977 the SIMM program (Solar Insolation Measurement, Montana) was initiated by Fowlkes Engineering under a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. Twenty instruments to measure solar radiation were sited across Montana during 1977 and an additional ten instruments were sited early in 1978. In addition to the thirty stations having continuous insolation recorders there are currently twenty-five stations which report the readings of manual instruments, Fig. 2.



● Continuous Data Recording Station
○ Manual Data Station'

Fig.2. Montana Solar Insolation Measurement Network

All of the instruments are located in public high schools. At each school there is a volunteer, usually a science teacher, who is responsible for the instrument. The volunteer periodically replaces the chart paper in the recorder and mails the completed strip charts to our office for processing. The total time required for the volunteer to do these tasks usually amounts to less than five hours each year.

The solar insolation strip chart recorders are often located in a laboratory, office, or classroom where they can be seen by the students. Some teachers make specific use of the insolation records in their classes.

All high schools participating in the SIMM program receive a copy of The Handbook of Solar Energy Experiments and a manual solar insolation meter. This Handbook was written by the author of this paper as an integral part of the insolation measurement program. The 80 page Handbook contains a review of solar basics and ten outlined experiments ranging from insolation measurement to testing a solar collector.

INSOLATION ON A TILTED SURFACE

Meteorological insolation data is usually recorded on a horizontal surface due, in part, to the fact that the solar collector of interest to meteorologists is the horizontal surface of the earth. For northern U.S. latitudes the solar designer will normally tilt the collector plane between 45° and 90° up from the horizontal to increase the average radiant flux density intercepted by the collector. Procedures exist for estimating the insolation on a tilted surface given the measured insolation on a horizontal surface. However, the net uncertainties of these estimates in northern U.S. latitudes during the winter will be around ± 20%. Some uncertainties arise from the pyranometer errors at low solar altitudes. Additional uncertainties exist due to reflected radiation from snow covered ground which will be intercepted by steep solar collectors but will not be intercepted by a horizontal radiation transducer.

Since the goal of the SIMM program is to develop a solar insolation data base for designing solar conversion devices we measure insolation on a surface tilted 60° up from horizontal and facing due south. The transducer hence becomes a model of a typical solar collector which might be used at this latitude to collect heat in the winter. The resulting 60° solar radiation data can often be used directly or can be transformed to neighboring tilt angles with relatively small increases in uncertainty. The effects of snow and dirt on a collector are approximately modeled by this transducer orientation and are an integral part of the insolation data.

INSTRUMENTATION

The solar insolation is sensed by a silicon cell mounted in an 8 cm square aluminum plate and covered with glass, shown in Fig. 3. The transducer is attached to a bracket outside the building and a wire runs to a strip chart recorder located inside the building. We fabricated all the transducers used in this program.

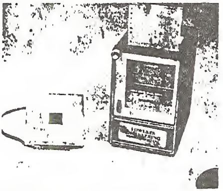


Fig. 3. Instrumentation for recording solar insolation

Silicon cell characteristics relating to solar flux measurement are well documented in the literature and several commercial silicon cell instruments are available (Selcuk, 1962). Briefly, the silicon cell characteristics causing departures from pyranometer readings are due to spectral response, temperature changes and cosine response. The spectral response will cause the silicon cell to read measurably higher on cloudy days and within 2 hours of sunrise or sunset. The instruments used in this program, for example, will read about 0.015 kW/m^2 high under conditions of 80% beam attenuation due to clouds. The amplitude error in this condition is ± 6%. The effect of this spectral error on the monthly average, daily total energy density is typically reduced to less than 3%. This reduced error is due to the relatively low energy density on cloudy days. Similarly, amplitude errors near sunrise and sunset have a small effect on daily total energy density: less than 2% on a clear day.

The published absolute accuracy of the strip chart recorders is 3%. This error is reduced significantly since the recorders are directly calibrated in conjunction with the transducers. The readability of the recorder during calibration, using a magnifier, is better than ± 1%.

The electrical circuit used is sensitive to changes in lead resistance. This factor has probably been the primary source of error in this measurement program. Resistance variations are usually due to improperly soldered lead wire connections. The gradually increasing contact resistance leads to a gradual reduction in sensitivity of the instrument. In a few cases this problem has been responsible for temporary errors of 10 and 20%. We are currently inspecting and servicing the instruments at all 30 stations.

DATA REDUCTION

Strip chart data is processed by tracing the curves on a digitizer platen connected to a microcomputer, Fig. 4. The resolution of the platen is 0.1 mm and each curve is represented by 200 to 400 coordinates. The reading error due to resolution is thus less than 1%. The primary source of data reduction error is the repeatability of the curve tracing itself. On clear days, where the curve is a well defined line, the reproducibility averages 1%. On cloudy days the reproducibility can reach 5 to 20%. This is due to the fast response of the silicon cell which produces a very rough, jagged curve on some cloudy days, Fig. 1.

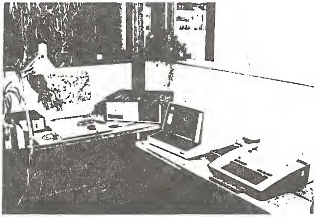


Fig. 4. Computer system used to read strip-charts and process solar insolation data

During the last year reproducibility tests have been run on over 800 data days (4% of our total data base). The reproducibility of the monthly average, daily total energy density averages better than ± 2%. These monthly values often reproduce within 1% due to the compensation of positive and negative errors when averaged.

The processed data from each day consists of day number, total energy density, day length, noon maximum intensity (if day was clear), intensity spectrum, half-hour average solar intensities, and a fault code (specifying lost or suspect data). The total energy is stored in 2 (8 bit)bytes and thus has a maximum resolution of 1 part in 512. All other non-integer quantities are rounded to integers and stored in a single byte in the file (maximum resolution 1 part in 256). The maximum loss of precision in this data due to rounding off is 0.5%.

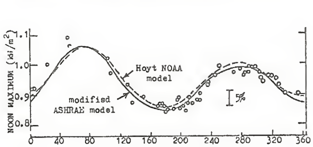
The data are stored on hard-sectored, 5½ inch magnetic diskettes using the North Star Disc Operating System (a popular microcomputer format). Each single-density diskette contains 3 station-years of solar data. This data has been used by Fowlkes Engineering as input to solar heating simulation models. Copies of these diskettes can be supplied at nominal cost for users wanting to implement their own simulation programs.

DATA ACCURACY

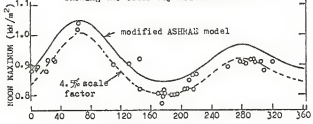
All transducers are calibrated in conjunction with the strip chart recorder by comparing the SIMM instrument to a Kipp or Eppley pyranometer on a clear day near noon. The calibration factor for each instrument is then determined from this comparison. Although this procedure established an initial calibration reference point it does not account for the effects of drift, aging, etc. which may occur on the site after the instrument is installed. For long-term control of data accuracy we make use of a clear day technique. This technique parallels the methods used by D.O.E. in their recent rehabilitation effort to create the SOLMET data base (DOE, 1979).

The essence of the clear day procedure is to compare the measured clear day radiation to the radiation predicted by a theoretical clear day model and then make appropriate corrections. We studied two clear day models. The first model was provided by Doug Hoyt of NOAA (Hoyt, 1978). This model was used in the SOLMET data rehabilitation. The second model was based on the ASHRAE procedure and constants with a clearness modification to account for altitude.

As part of our data reduction procedure we pick off the maximum radiation at solar noon on all clear days and store this value on the computer. The ASHRAE clear day calculations were also programmed on our computer. Doug Hoyt provided us with clear day noon maximums from his model for a 60° tilted surface. A graph of these two clear day models along with experimental clear day values are shown in Fig. 5a for Great Falls, Montana. Based on this comparison we concluded that the modified ASHRAE clear day model could be used to maintain the integrity of our data.



(a) Gt. Falls data for 1978
showing two clear-day models with data



(b) Glendive data for 1978
illustrating use of scale factor

Fig. 5. Comparison of clear day experimental and theoretical values

The clear day procedure is used to evaluate all of our data. If the experimental clear day values are consistently in disagreement the data is scaled by an appropriate correction factor. An example of this is given in Fig. 5b for Glendive, Montana. In this case the experimental clear day values appeared uniformly low by 4.5% and all the Glendive data for that year was therefore scaled up by 4.5%. The net effect of this procedure is to insure that large errors do not occur due to instrumentation calibration drift.

DATA OUTPUT

The solar insolation data output from this program has been summarized in the Montana Solar Data Manual which will be distributed to libraries, extension services, engineers, architects and solar designers this summer. This Manual includes the two years of solar insolation data collected to date for all the stations in the network. Data on the frequency of occurence of cloudy days has also been included to aid in the sizing of heat storage systems. Average climatological data from National Weather Service records is reproduced in the Manual for the convenience of the designer. Also included in the Manual is a brief review of solar design methods, economic analysis, a list of references, conversion tables and a discussion of the accuracy of the solar data.

The solar data is presented in tables in the form of weekly and monthly averages of the daily total energy density for each station. Also given is the average intensity spectrum of the daily total. This is presented as a percentage of the daily total energy density which occured at radiation intensities above 12 threshold values ranging from 0.1 to 1.2 kW/m². Due to losses, solar collectors require a radiation of some minimum intensity before they can produce positive output. This threshold may be from 0.1 to 0.4

SOLAR RADIATION DATA for: HELENA, MONTANA 1978

Montana Department of Natural Resources and Conservation
compiled by: Fowlkes Engineering, Bozeman, Mt.

WEEK STARTING	DAILY AVERAGE KWH/SM/DAY	PER CENT TOTAL ENERGY ABOVE THRESHOLD (KW/SM) >.1	>.2	>.3	>.4	>.5	>.6	>.7	>.8	>.9	>1.0	>1.1	>1.2
JAN 1	3.14	91	71	56	54	40	39	36	26	10	4	0	0
JAN 8	1.77	81	50	32	29	26	18	9	9	2	0	0	0
JAN 15	(3.56)	95	86	73	57	53	49	42	32	10	10	2	0
JAN 22	2.16	80	50	31	28	26	23	17	17	7	6	2	0
JAN 29	3.10	94	80	61	53	39	29	25	19	9	7	0	0
FEB 5	2.37	80	66	43	31	28	23	16	13	9	6	0	0
FEB 12	(4.07)	96	90	79	72	59	49	42	33	10	9	0	0
FEB 19	4.70	97	91	78	69	57	51	43	35	24	15	2	0
FEB 26	4.91	96	89	80	72	66	54	45	39	25	16	0	0
MAR 5	5.19	97	90	83	75	65	58	52	40	26	14	1	0
MAR 12	4.14	95	85	70	57	45	37	34	27	7	4	0	0
MAR 19	(4.39)	95	88	78	74	58	46	34	21	7	0	0	0
MAR 26	4.42	94	82	69	59	50	39	30	20	12	4	0	0
APR 2	3.79	85	75	65	59	50	42	31	20	16	6	0	0
APR 9	5.53	96	92	86	82	72	62	54	37	27	15	0	0
APR 16	4.63	94	88	75	58	48	40	36	28	19	9	0	0
APR 23	5.04	95	89	80	71	61	49	39	27	10	1	0	0
APR 30	2.68	76	53	34	23	20	17	9	3	1	0	0	0
MAY 7	4.33	94	85	69	56	47	37	26	20	9	0	0	0
MAY 14	3.76	75	70	62	49	38	31	20	14	3	1	0	0
MAY 21	(3.45)	87	67	49	41	33	23	20	11	2	0	0	0
MAY 28	(4.13)	87	73	58	55	50	41	31	18	0	0	0	0
JUN 4	5.72	94	87	80	72	62	53	40	22	1	0	0	0
JUN 11	5.30	94	89	84	75	69	59	47	28	1	0	0	0
JUN 18	4.57	93	85	76	66	56	46	33	17	8	6	0	0
JUN 25	4.37	93	82	68	62	53	50	40	16	0	0	0	0
JUL 2	3.30	89	71	63	57	47	32	21	9	2	0	0	0
JUL 9	5.65	95	92	87	80	73	63	51	33	3	0	0	0
JUL 16	4.39	94	84	71	59	52	44	35	27	1	0	0	0
JUL 23	5.47	94	91	87	81	71	64	53	35	9	0	0	0
JUL 30	5.67	96	92	87	83	73	65	56	30	1	0	0	0
AUG 6	5.01	97	94	88	83	74	65	56	36	0	0	0	0
AUG 13	3.45	80	73	57	46	38	30	22	14	6	1	0	0
AUG 20	5.40	96	91	86	79	70	59	50	40	23	1	0	0
AUG 27	5.51	97	93	83	78	71	61	49	30	22	0	0	0
SEP 3	4.45	93	83	76	68	58	55	48	27	22	0	0	0
SEP 10	3.47	71	50	47	46	39	32	28	22	14	9	1	0
SEP 17	4.56	82	77	69	61	54	48	42	35	29	23	1	0
SEP 24	5.46	95	87	83	78	71	63	51	40	29	7	0	0
OCT 1	6.00	98	96	89	81	77	69	56	42	26	5	0	0
OCT 8	5.62	98	95	90	84	74	65	53	40	25	6	0	0
OCT 15	4.52	95	89	80	73	65	55	45	39	23	7	0	0
OCT 22	4.45	95	88	80	72	59	55	44	31	19	3	0	0
OCT 29	4.63	90	79	75	69	61	60	52	42	28	4	0	0
NOV 5	2.93	79	71	64	55	45	36	27	13	7	3	0	0
NOV 12	2.64	83	55	46	39	33	31	24	20	13	1	0	0
NOV 19	2.11	75	58	46	34	30	23	18	9	6	2	0	0
NOV 26	2.42	90	63	48	43	39	26	25	18	12	4	0	0
DEC 3	1.75	71	47	30	22	19	17	16	13	6	0	0	0
DEC 10	3.23	94	80	72	67	53	42	37	29	8	0	0	0
DEC 17	2.11	70	59	47	37	37	26	20	17	7	0	0	0
DEC 24	2.09	83	75	61	56	47	43	37	26	10	2	0	0

Fig. 6. Sample solar data from manual

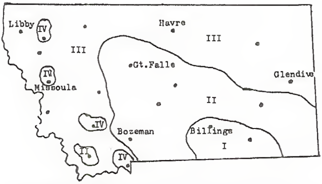
kW/m^2 depending on the collector design and ambient temperature. Given the threshold for the collector the corresponding percentage may be read from the spectrum table. This percentage multiplied by the total energy density will represent the maximum useable solar energy available to the collector.

Figure 6 reproduces a page of weekly average data from the Montana Solar Data Manual for Helena, Montana during 1978. The first column lists the starting date for the week and the second column lists the average daily total energy density, kW-hr/m^2-day, during that week. The next twelve columns list the average spectrum during the week. Similarly, more compact tables listing monthly averages are also included in the Manual. Parentheses around the daily averages denote that at least one day of data was missing during the averaging period.

The current Manual contains solar data from the first two years of the measurement program, 1977 and 1978. These measurements are being continued through the next year and the Data Manual will be updated at that time. Assuming funds are available, this program will be continued to a point where long-term average insolation data can be reliably documented.

RELATIVE SOLAR POTENTIAL

The solar data for the last two years has been summarized to give a preliminary overview of the relative potential for solar utilization in Montana. Solar insolation data and long-term average degree-day data were averaged for the 8 month heating season, October through May. The average solar insolation was multiplied by an efficiency factor and then divided by the total heating season degree-days. The efficiency factor was derived for each station based on a nominal collector efficiency curve. These efficiency values were similar for all stations. In areas with high relative solar potentials, a given collector design would supply a higher percentage of the annual heat load. Further refinement of the solar potential of different areas of Montana will require both more detailed models and a larger solar insolation data base. The current results are presented in Fig. 7.



I=0.40-0.46, II=0.35-0.39, III=0.30-0.34, IV=0.20-0.29

Fig.7. Map showing four regions of relative solar/load ratio

ACKNOWLEDGEMENTS

This measurement program is funded by a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. The support and advice of Dana Gunderson, Administrative Officer, is acknowledged. The assistance of the volunteers at the measurement stations is crucial to the success of this program and their contributions are gratefully acknowledged.

Several members of the staff at Fowlkes Engineering have contributed to this solar measurement program and this paper. Pat Sullivan has carefully logged and organized strip chart records for over 15,000 data days. Pat also typed this paper and made editorial corrections. Sharon Kleingartner is acknowledged for her important role in entering the data into the computer for processing. Kellee Crisafulli and Rose Nelson have written numerous computer programs to process and verify the solar data.

REFERENCES

Fowlkes, Charles W., Montana Solar Data Manual, available from Montana Dept. of Natural Resources & Conservation, Alternative Renewable Energy Sources Program, 32 S. Ewing, Helena, MT 59715, 1979.

Hoyt, Douglas V., "A Model for the Calculation of Solar Global Insolation", Solar Energy, Vol. 21, No. 1 (1978)

Selcuk, K. and Yellott, J. I., "Measurement of Direct, Diffuse, and Total Solar Radiation with Silicon Photovoltaic Cells", Solar Energy, Vol. 6, No. 4 (1962)

U. S. Dept. of Energy-Div. of Solar Technology, "Hourly Solar Radiation-Surface Meteorological Observations", SOLMET Final Report, Vol. 1 (1979)

EXHIBIT IV: SOLAR RADIATION OBSERVATION STATIONS

TATION LOCATION	RADIOMETER TYPE, MFG. MODEL	RECORDER RECORD FORM	PERIOD OF RECORD
	MISSISSIPPI		
CANTON N 32°36' W 90°02' 69 M LOCKHEED	PYRANOMETER, EPPLEY PSP (T)	MICROCOM DEC	3/78 -
MISSISSIPPI STATE N 33°28' W 88°48' 122 M MS STATE UNIV	PYRANOMETER, EPPLEY	STRIP CHART LEEDS & NORTH	
	MISSOURI		
ST. LOUIS EPA	PYRANOMETER, EPPLEY PYRGEOMETER, EPPLEY PYRHELIOMETER, EPPLEY	MAG TAPE	7/72 -
	MONTANA		
ANACONDA N 46°07' W112°57' 1625 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
BILLINGS N 45°47' W108°30' 950 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -

STATION LOCATION	RADIOMETER TYPE, MFG. MODEL	RECORDER RECORD FORM	PERIOD OF RECORD
	MONTANA (CONTD)		
Bozeman N 45°40' W111°02' 1449 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Browning N 48°33' W113°01' 1360 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Butte N 46° W112°30' 1754 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Chcteau N 47°49' W112°12' 1158 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Colstrip N 45°53' W106°38' 774 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Dillon N 45°15' W112°38' 1541 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Ennis N 45°21' W111°44' 1502 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -

TATION LOCATION	RADIOMETER TYPE, MFG. MODEL	RECORDER RECORD FORM	PERIOD OF RECORD
	MONTANA (CONTD)		
FORT BENTON N 47°48' W110°40' 792 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
GLASGOW N 48°12' W106°38' 639 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
GLENDIVE N 47°07' W104°44' 631 M E	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
GREAT FALLS N 47°31' W111°18' 1015 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
HAMILTON N 46°15' W114°09' 1097 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
HARLOWTON N 46°26' W109°50' 1270 M FE	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -
HAVRE N 48°34' W109°40' 38 M E	PYRANOMETER (T) SILICON - SIMM - IR	STRIP CHART RUSTRACK RECORDER (15)	1977 -

MONTANA
(CONTD)

STATION LOCATION	RADIOMETER TYPE, MFG. MODEL	RECORDER RECORD FORM	PERIOD OF RECORD
Helena N 46°35' W112°02' 1257 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Jordan N 47°19' W106°54' 853 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Kalispell N 48°13' W114°16' 902 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Lewistown N 47°04' W109°25' 1207 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Libby N 48°24' W115°35' 626 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Livingston N 45°39' W110°34' 1369 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Miles City N 46°25' W105°49' 72 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -

TION LOCATION	RADIOMETER TYPE, MFG. MODEL	RECORDER RECORD FORM	PERIOD OF RECORD
	MONTANA (CONTD)		
Missoula N 46°52' W114° 982 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Plentywood N 48°47' W104°34' 617 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Polson N 47°41' W114°10' 899 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Red Lodge N 45°11' W109°15' 1691 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Sidney N 47°42' W104°10' 588 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
Thompson Falls N 47°35' W115°20' 751 m FE	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -
West Yellowstone N 44°55' W111°04' 31 m	Pyranometer (T) Silicon - SIMM - IR	Strip chart Rustrack Recorder (15)	1977 -

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80302

EXHIBIT V: NOAA CALIBRATION

RADIATION INSTRUMENT CALIBRATION

SERIAL NO. (None)

INSTRUMENT TYPE Pyranometer

MANUFACTURER Fowlkes Eng.

MODEL Photocell

THIS INSTRUMENT HAS BEEN COMPARED WITH A NOAA REFERENCE STANDARD

THE DERIVED CONSTANT IS:

80.3 x 10^{-6} volts/watt meter^{-2}

56.0 millivolts/langley min^{-1}

ON THE ABSOLUTE RADIATION SCALE 1975

April 10-19, 1979
DATE OF TEST

Edwin C. Flowers
Edwin C. Flowers
SOLAR RADIATION FACILITY

Calibration performed for:

Charless W. Fowlkes
31 Gardner Park Drive
Bozeman, MT 59715

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES
Boulder, Colorado 80302

January 1, 1977

Calibrations performed by the Solar Radiation Facility are on the Absolute Radiation Scale. This scale is embodied in the instrument PACRAD III, an active cavity radiometer maintained by the World Radiation Center, Davos, Switzerland. (For reference see: Pyrheliometer Comparisons Davos, 1975, Results, Working Report No. 58, Swiss Meteorological Institute Zurich, Switzerland, 1976.)

The relationship between calibration factors based on the Absolute Radiation Scale (ABS) and factors based on the International Pyrheliometric Scale (IPS) as maintained by NOAA, is:

$$C_{(ABS)} = 0.975\ C_{(IPS)}$$

This means that measurements made with instruments calibrated by NOAA on the IPS will yield irradiance values approximately 2.5% lower than measurements made with instruments calibrated by NOAA on the Absolute Scale.

Edwin Flowers, Chief
Solar Radiation Facility

FINAL REPORT

TO

DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION
ALTERNATIVE RENEWABLE ENERGY SOURCES PROGRAM

FOR

SOLAR INSOLATION MEASUREMENT, MONTANA

GRANT RAE 140-782

Effective Date: 4/17/79

from

Fowlkes Engineering
31 Gardner Park Drive
Bozeman, MT 59715

Respectfully submitted,

Charles W. Fowlkes
Charless W. Fowlkes

July 1980

1.0 INTRODUCTION

The emphasis during the third year of the Solar Insolation Measurement, Montana (SIMM) program has been to (a) continue the solar data collection process, (b) make the current data available to the public and (c) document the quality and accuracy of the data. Specific milestones and exhibits are included in this report to demonstrate these accomplishments.

2.0 BUILDING THE DATA BASE

During the grant year over 9,000 charts of daily solar radiation were collected from thirty stations in the field. These charts were checked for errors, analyzed, read onto a computer system and filed for future reference. The computer data base was subsequently checked for errors and archive copies of the data were made and stored.

This data was output in the form of tables of solar radiation and cloud cover at each of the thirty sites. The tables were reproduced and bound to form the 1979 Addendum to the Montana Solar Data Manual. Three hundred copies of the Addendum were delivered to the Department of Natural Resources and Conservation as part of the grant agreement. Exhibit I is a copy of this document.

3.0 INSTRUMENT MAINTENANCE

Throughout the year the instruments in the field were repaired and maintained. Some of the recorders have run continuously for three years at this point and occasionally motors will burn out or the chart drive linkage will fail. Part of the maintenance program includes routine phone calls to the volunteers. During the summer of 1979 a technician visited all 30 sites in person. He performed routine maintenance and checked the orientation and calibration of the solar recorders. Details of the installation were documented on the form shown in Exhibit II.

4.0 TECHNICAL PRESENTATIONS

Technical papers on this solar measurement program were presented and published at two national conferences: Solar Northwest 79 in Seattle and the annual International Solar Energy Society meeting in Phoenix in 1980. These presentations have allowed a wide audience of solar experts to review our methods and results. Their response has been favorable. A reprint of the most recent paper is given in Exhibit III. This paper provides a good, brief description of the program.

5.0 SOLAR DATA MANUAL DISTRIBUTION

During the past year the Manual has been sent to individuals outside the state in order to solicit their comments and criticism. This has the effect of calling attention to our program and gaining the benefits of expert criticism which will improve the program. A distribution list and some typical comments are included as Exhibit IV.

6.0 EXTRA REPRINTS OF MONTANA SOLAR DATA MANUAL

At the request of John Orndorff, sixty additional copies of last year's Montana Solar Data Manual were reproduced. The initial printing of 350 copies had been exhausted. This activity was not included in the original contract or budget but sufficient funds were gathered from various budget categories to pay for this work. These copies were delivered to the Department of Natural Resources and Conservation in June 1980.

7.0 DATA PROCESSING

The computer hardware and software were altered to increase the efficiency and accuracy of the solar data processing. We now have a hard copy of the data for each solar radiation curve as it is read into the system. This change of format gives convenient running documentation of the data base which is kept on file. A sample of this output is shown in Exhibit V.

8.0 DATA ACCURACY

Our solar transducer has been calibrated on two separate occasions by Ed Flowers at the NOAA laboratories in Boulder. I was able to visit the laboratory and discuss the results during October 1979. The NOAA calibration sheet is shown in Exhibit VI.

9.0 CLEAR DAY MODEL

An improved implementation of Douglas Hoyt's clear-day radiation model was generated during the past year. This model is now implemented on the same computer that we use to compile the solar radiation data. In previous years we used output from NOAA's computer. Now we can produce original comparisons for all sites right in the office. Our version has been compared to the original NOAA version for Great Falls, Montana and it agrees to within less than one percent. A listing of this program is shown in Exhibit VII.

10.0 FUTURE PROJECTS

We are continually looking for ways to improve the accuracy and efficiency of our task of measuring and documenting the solar energy resource in Montana. We are currently evaluating the feasibility of using a solar radiation instrument which incorporates digital recording in place of analog chart recording. We hope to have a prototype ready for evaluation this year.

We have initiated a comparison of our solar measurements with two other Montana stations that are part of the National Solar Data Program. Initial comparisons show that we are in very close agreement. This comparison will be extended and analyzed during the coming year.

11.0 FINAL BUDGET

An itemized final budget report is shown in Exhibit VIII. The expenditures at the end of the grant totaled $34,794.00 leaving a net surplus of $971 that was not used.

Reprint from the *PROCEEDINGS OF THE SIXTH NATIONAL PASSIVE SOLAR CONFERENCE*
Published by the American Section of the International Solar Energy Society,
205B McDowell Hall, University of Delaware, Newark, DE 19711

INTERFACING A $10 CALCULATOR FOR DATA ACQUISITION

Charless W. Fowlkes, Ph.D., P.E.
FOWLKES ENGINEERING
31 Gardner Park Drive
Bozeman, MT 59715

ABSTRACT

Low cost instruments that can be used to make measurements around solar projects are of interest to homeowners and solar energy experimenters. For solar house performance monitoring it is important to know the total solar radiation intercepted by the collector and the total accumulated degree days. A number of excellent instruments are available which will integrate and display these quantities, but their cost may exceed the individual experimenter's budget.

We have recently built a circuit which requires less than $20 worth of parts and uses a Texas Instruments hand calculator, costing about $10, for a read-out. This device can be connected to a manufactured or home-made solar radiometer to accumulate and display total solar radiation. Another application of the same basic circuit uses two temperature probes to effect a degree-day integrator for heat loads or for a wood stove integrator. The calculator alone can be used as an event counter to display pump cycles, door openings, etc.

1. INTRODUCTION

Some hand calculators can be adapted for use as a low frequency counter. Any calculator which will increment the display in response to a single key stroke can be used. The Texas Instruments TI-1010 used in our experiments will add a constant to the display when the [=] key is pressed. For example:

Keystroke	Display
[+] [1] [=]	1
[=]	2
[=]	3
etc.	
Or	
[+] [.25] [=]	.25
[=]	.50
[=]	.75
etc.	

Pressing a key on a calculator closes a switch under the key. The procedure used to interface the calculator as a counter is basically: (a) Identify the key which, when pressed, adds a constant to the display (the [=] key in the example above), (b) locate the two sides of that switch in the calculator keyboard circuitry, (c) solder a wire to each side of that switch and (d) lead the wires to an external switch. This external switch, which is in parallel with the internal keyboard switch, will now increment the display, effecting a slow speed counter. The external switch can be a mechanical switch such as a microswitch, a relay or a mercury switch. It can also be an electrical switch such as a transistor, photo transistor or Hall effect device.

The maximum frequency that can be counted is determined by the keyboard scan frequency of the particular calculator, which is usually between 5 and 100 Hz. The display may only respond up to about 5 Hz if it is a liquid crystal type (LCD). The person reading the display may only respond up to one to two Hz, which sets the maximum frequency of the system.

At this point the calculator could be connected to a switch on a door, a vent, a movable insulation system, a solar circulating pump or a ventilation fan and it would display or "count" openings, on-times, etc. In this application a mechanical counter might be used with equal cost and reliability.

The electrical signals from temperature transducers, solar cells, pressure transducers, heat flow sensors, etc., usually consist of a voltage or current which varies in direct proportion to the physical quantity being sensed. There exist a number of integrated circuit chips which will convert a dc input voltage into a proportional pulse (or switch closure) frequency on the output. These devices are called voltage-frequency (V-F) converters.

By adding an appropriate V-F converter, we can now use the calculator to display the integrated total of a variety of physical parameters. The steps of the process are: (a) convert the physical parameter to a proportional voltage, (b) convert this voltage into a proportional frequency of switch closures and (c) count the switch closures with the modified calculator using the "constant add" feature.

2. TRANSDUCERS

Solar radiation and temperature are two important parameters which may be used to characterize the performance of solar heated buildings. A low cost solar radiation transducer can be constructed with a silicon cell and a wire-wound shorting resistor. A cell having 3.5 cm^2 area and a 1Ω shorting resistor will produce about 80 mV output in bright sun. Properly calibrated and tilted toward the sun (at typical solar collector angles), this device will have an average accuracy approaching ± 5% in measuring daily total insolation. Commercial solar transducers may also be used with this calculator circuit. Their accuracy will be somewhat higher but their cost will be much higher.

The differential temperature circuit included in this paper uses two AD590 transducers manufactured by Analog Devices. These transducers are connected to produce a voltage proportional to the difference in temperature. Since the calculator will only count or integrate in a forward direction, one probe is identified as the "hot" probe and the other as the "cold" probe. The count will thus be proportional to the degree-hours for all $T_{hot} > T_{cold}$. If the hot probe is placed inside the house and the cold probe placed outside, the calculator will accumulate actual heating degree-hours. If the probes are reversed, the calculator registers cooling degree-hours.

3. HARDWARE

3.1 Interfacing the TI-1010

Gently pry the back off the TI-1010. Lay the calculator on its face and slightly lift the bottom of the flexible printed circuit to expose the terminals on the keyboard (see Fig. 1). Solder a wire to the farthest left terminal. This wire should be connected to pin 3 of IC1. Solder another wire to the second terminal from the right. This wire should be connected to ground. A small hole may be drilled in the back of the calculator case to allow the wires to exit and the case to close.

TABLE 1
PARTS LIST

R_1, R_2, R_4, R_9	10K 1%	C1	.22ufd Mylar
R_3, R_7	100K 1%	C2	.0047ufd Mylar
R_5	2.2K 1%	C3	.01ufd Mylar
R_6, R_8	1.21M 1%	C4, C5	10ufd Electrolytic
R_{10}, R_{11}	28.7K 1%	IC1	LM331
R_{12}	20K ten-turn	IC2	LM108A
D1	1N4148	IC3	ICL7660
VR1	LM7805		

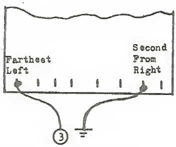


Fig. 1. Backside of TI-1010

3.2 Circuit Operation

The voltage to frequency circuit is shown in Fig. 2. An operational amplifier (IC2) is configured as an integrator using C2 as its feedback capacitor. The charge rate of C2 is controlled by $-V_L$, the voltage across the load resistor (R_L) and R6. R7 to R12 provide an offset voltage for IC2. When C2 is charged to the threshold set by the voltage divider consisting of R1 and R2, the frequency to voltage converter (IC1) produces a switch closure between pin 3 and ground. A TI-1010 calculator can be connected to count and display the number of pulses. R3 and C1 are the reset timing circuit.

Fig. 2 also shows the power supply for this circuit. A power supply of 6V dc or greater is required. VR1 regulates this to 5V dc, and IC3 converts the 5V dc to -5V dc. Power consumption of this circuit is only 9.2 ma (9.7 ma with two temperature transducers) and can be powered for over 30 hours of intermittent use with a 9V transistor battery. For long term use, get an inexpensive power supply to replace the battery. A 6V dc supply rated @ 100 ma (the cube-plug type sold for transistor radios) is more than sufficient. A parts list is shown in Table 1.

Fig. 3 shows a completed instrument which incorporates both the silicon cell and differential temperature inputs. The desired input is selected with a switch. (This unit was built as a test prototype and is not entirely practical because each input will have a different zero-offset.) The photograph shows a 9V battery powering the circuit for portability. The cube-plug shown in the photograph can also be used to power the circuit.

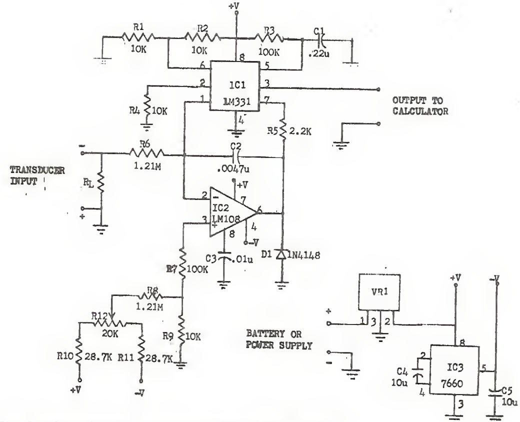


Fig. 2. Voltage-frequency converter and power supply circuits.

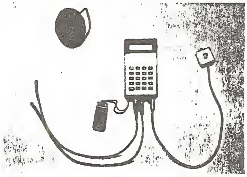


Fig. 3. Completed prototype

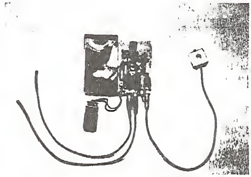


Fig. 4. Case opened to show prototype circuit.

It is a nominal 6V unit which costs a few dollars at a local store.

The circuit can easily be wired on a piece of perf board about the size of the calculator. We put the prototype circuit in a standard audio cassette case and attached the calculator to the lid of the case. This was convenient as the lid of the case could be opened to access the circuit for checkout and zero adjustment. A photograph with the cover opened is shown in Fig. 4. When using a solar cell as an input device, R_L must be approximately .3Ω. The solar cell must be connected with the positive terminal to ground, Fig. 2.

When using temperature transducers as input devices, R_L should be selected as follows:

For temperature differentials of 0–5° C, $R_L \sim 5K\Omega$.

For temperature differentials of 0–25° C, $R_L \sim$ [illegible].

The "cold" temperature probe must have +5V dc on the positive lead and the "hot" probe must have -5V dc on the negative lead. Fig. 5 shows this input circuit.

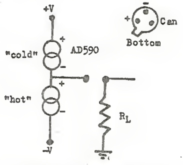


Fig. 5. Differential temperature input circuit.

4. USING THE CIRCUIT

Normal precautions should be taken before connecting power to the circuit. After the circuit has been built and de-bugged, the following procedures will prepare the instrument for use.

4.1 Adjusting the Offset Voltage

With silicon solar cell as input device:

1) Short the input load resistor R_L.
2) Connect a voltmeter to pin 6 of IC2. The charging ramp of C2 should be observed. The voltage should be between approximately -.6 and 2.5V dc.
3) If the voltage is constant, adjust R12 until the ramp begins to cycle. Note the value of the peak voltage.
4) Slowly adjust R12 until the ramp voltage holds steady at about 0.1V below the peak (i.e. if the peak is 2.5V, adjust R12 until the voltage is steady at 2.4V.

With AD590 temperature probes as input device:

1) Immerse both of the AD590 temperature probes in an ice bath and allow their temperature to stabilize.
2) to 4) This procedure the same as above.

4.2 Calibration with Silicon Solar Cell

If you do not have a reference pyranometer, the following clear day procedure should allow calibration to within ± 10% or better.

Calibration should be done on a clear day within one hour of solar noon.

1) Set the offset voltage as described in Section 4.1.
2) Turn on calculator and key in [+] [1].
3) Hold the solar cell normal to the sun (directly facing the sun).
4) Record the calculator count and begin a one minute test. After one minute record the new count. NOTE: If the calculator count is too rapid to read, the size of the load resistor (R_L) should be decreased.
5) Look up the Beam Radiation at solar noon, I, for your latitude from Table 2.
6) Add 1% to I for each 1000 feet of elevation above sea level. Add 3% for a very clear (arid or mountain) atmosphere. Subtract 5% for coastal or polluted atmospheres.
7) The solar calibration constant is

$$\frac{(\mathrm{I})\,\mathrm{kW/m^2}}{\mathrm{count/min}} \times \frac{\mathrm{hr}}{60\ \mathrm{min}} \times \frac{1000\mathrm{W}}{\mathrm{kW}}$$

$$= \frac{16.7 \times \mathrm{I}}{\Delta\ \mathrm{count}}\ \mathrm{Wh\text{-}m^{-2}}$$

Example: In one minute 60 counts were recorded. From Table 2 for the month of June and 40° North Latitude, I=0.88. Elevation is 3000 feet, therefore:

$$\mathrm{I} = 0.88 + (0.03 \times 0.88) = 0.906$$

An additional 3% is added for a very clear atmosphere:

$$\mathrm{I} = 0.906 + (0.03 \times 0.88) = 0.931\ \mathrm{kW\text{-}m^{-2}}$$

$$\text{Constant} = \frac{16.7 \times 0.931\ \mathrm{Wh\text{-}m^{-2}}}{60\ \text{counts}}$$

$$= 0.26\ \mathrm{Wh\text{-}m^{-2}\text{-}ct^{-1}}$$

8) To use the device, key in [+] [.26]. The display will now accumulate $\mathrm{Wh\text{-}m^{-2}}$ of radiation falling on the silicon cell. Any convenient units can be used

TABLE 2
NORMAL BEAM RADIATION AT SOLAR NOON ($\mathrm{kW\text{-}m^{-2}}$)

	24° LAT	32° LAT	40° LAT	48° LAT
JAN	1.01	0.98	0.93	0.84
FEB	1.02	1.00	0.97	0.93
MAR	1.00	0.99	0.97	0.94
APR	0.94	0.94	0.92	0.91
MAY	0.91	0.90	0.90	0.88
JUN	0.89	0.88	0.88	0.87
JUL	0.88	0.88	0.87	0.86
AUG	0.90	0.90	0.88	0.86
SEP	0.95	0.93	0.91	0.88
OCT	0.98	0.96	0.93	0.88
NOV	0.99	0.96	0.91	0.82
DEC	1.00	0.96	0.90	0.79

by simply keying in the appropriate constant.

4.3 Calibration with Temperature Probes

1) Set the offset voltage as described in Section 4.1.
2) Turn the calculator on and key in [+] [1].
3) Select two water baths with temperatures differing approximately by the amount corresponding to the load resistor (R_L) being used (i.e. 25° C for R_L = 1K).
4) Immerse the "cold" probe in the cooler bath and the "hot" probe in the warmer bath and allow to stabilize.
5) Record the calculator count and begin a one minute test. After one minute record the new count. NOTE: If the calculator count is too rapid to read, the temperature differential or the size of the load resistor (R_L) should be decreased. If the count appears very sluggish (i.e. only 10 counts per minute), the temperature baths may have too small a temperature differential or R_L should be increased.
6) Record the temperature of the "cold" bath (T_c) and the temperature of the "hot" bath (T_h).
7) The calibration constant = $\dfrac{T_h - T_c}{\text{count/min}}$

   Example: In one minute 60 counts were recorded. The temperature of the cold bath (T_c) was 0° C and the temperature of the hot bath (T_h) was 25° C.

   $$\text{Constant} = \frac{(25-0)^\circ\text{C}}{60 \text{ counts/min}} = 0.4167^\circ\text{C-min/ct}$$

8) To use the device, clear the display and key in [+] [.4167]. The display will now accumulate °C-min when $T_h > T_c$. The constant can be converted to display other convenient units. For example, $0.4167 \times 1.8/60 = 0.0125$ °F-hr/count.

5. RECOMMENDATIONS

We have built two of these circuits and they have worked. The design should be considered as a prototype and the user should be prepared for possible bugs that we may have overlooked. The TI-1010 calculator that we used for the prototypes will automatically turn itself off after several minutes of no keyboard entry. Another calculator without this feature would have to be used for long time measurements.

A test of the temperature stability of the circuit we built showed that the drift was less than 1%/10°C. No controlled, long-time reliability tests have been run.

References (1) and (2) will be helpful to anyone wanting to explore other applications which use calculators to display physical measurements. Reference (3) discusses details of using low-cost silicon cells to measure insolation. References (4) and (5) discuss performance monitoring of solar houses using instruments of moderate cost and may be of interest.

The parts for this circuit can be ordered from Jameco, TriTek, Electrolabs, or other selected mail order electronics parts houses. The addresses of electronic parts suppliers can be found in advertisements in most hobby electronics or computer magazines.

6. ACKNOWLEDGEMENTS

The resources in References (1) and (2) were helpful in initiating this construction project. Carlos Lozano wired and tested the prototypes described in the paper. Carlos also outlined the calibration procedures and prepared the circuit diagrams given in the paper. His contributions are gratefully acknowledged. Jody Martinson typed the final manuscript and made editorial corrections.

7. REFERENCES

(1) Adler, Carl G., "An Inexpensive Insolation Integrator with Printing Capability", Proceedings of the 1980 Annual Meeting, AS/ISES (1980).

(2) Johnson, Ben, Application Notes, RC-111, KALTEK Calculator Technology, Box 7462, Rochester, NY 14615 (1981).

(3) Fowlkes, Charles W., "Controlling the Accuracy of Solar Radiation Data from a Low Cost, 30 Station Network", Proceedings of the Sixth National Passive Solar Conference, AS/ISES (1981).

(4) Fowlkes, Charles W., "Practical Solar Performance Monitoring", Proceedings of the 1980 Annual Meeting, AS/ISES (1980).

(5) Fowlkes, Charles W., "Experimental Problems in Measuring the Thermal Performance of Passive Solar Systems", Proceedings of the Fifth National Passive Solar Conference, AS/ISES (1980).

Reprint from the *PROCEEDINGS OF THE SIXTH NATIONAL PASSIVE SOLAR CONFERENCE*
Published by the American Section of the International Solar Energy Society,
205B McDowell Hall, University of Delaware, Newark, DE 19711

CONTROLLING THE ACCURACY OF SOLAR RADIATION DATA FROM A LOW COST, 30 STATION NETWORK

Charlees W. Fowlkes, Ph. D., P.E.
Fowlkes Engineering
31 Gardner Park Drive
Bozeman, MT 59715

ABSTRACT

For the past four years in Montana we have operated a network of 30 low-cost solar radiation measuring instruments (1). At this point the data base consists of over 40,000 data days. The basic element of data stored on the computer is the half-hour average, radiant intensity on a 60° tilted surface. The sensors are silicon cells mounted on a flat plate and connected to a strip chart recorder. The cost of each instrument at the beginning of the SIMM program was about $200.

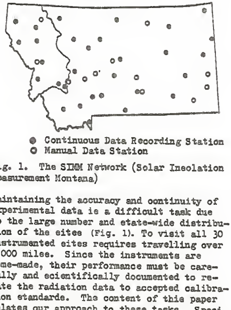


Fig. 1. The SIMM Network (Solar Insolation Measurement Montana)

Maintaining the accuracy and continuity of experimental data is a difficult task due to the large number and state-wide distribution of the sites (Fig. 1). To visit all 30 instrumented sites requires travelling over 3,000 miles. Since the instruments are home-made, their performance must be carefully and scientifically documented to relate the radiation data to accepted calibration standards. The content of this paper relates our approach to these tasks. Specifically, the results of (a) NOAA calibrations, (b) side-by-side pyranometer comparisons, (c) clear day theoretical comparisons and (d) comparison with independent measurements from the National Solar Data Network are discussed. The results of each approach in assessing accuracy and maintaining data integrity of the SIMM instruments is discussed.

1. INTRODUCTION

The instruments are mounted on public high schools throughout Montana. This program uses volunteers, typically high school teachers, who help maintain the instruments in the field. The strip chart records are mailed by the volunteers to our office where they are traced on a digitizer for input into a microcomputer.

The output of our solar measurement program is published annually in the Montana Solar

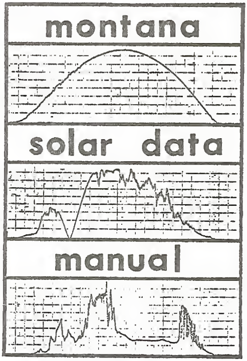


Fig. 2. Cover of Montana Solar Data Manual, illustrating insolation records (including eclipse on 2/26/79)

Data Manual (2). This manual addresses an audience that ranges from technical and professional people to individual homeowners, backyard inventors and solar enthusiasts. The manual reports insolation data and cloudy day statistics. Climatological data, solar design methods and a selected bibliography are also included in the manual. The manual is distributed free by the sponsoring agency, Alternative Renewable Energy Sources Program, Montana Department of Natural Resources and Conservation. About 500 copies of the manual have been distributed to libraries, universities and designers. Another 500 copies of a revised and updated manual are being prepared for distribution during the summer of 1981. The SIMM network is in its fifth year.

2. DATA REDUCTION ERROR

Strip chart data is processed by tracing the curves on a digitizer platen connected to a microcomputer. The resolution of the platen is 0.1 mm and each curve is represented by 200 to 400 coordinates. The reading error due to resolution is less than 1%. The primary source of data reduction error is the repeatability of the curve tracing itself. Reproducibility tests have been run on over 1,000 data days. The reproducibility of the monthly average insolation is always ± 2% and often within 1%.

3. TRANSDUCER ERRORS

The SIMM silicon cell transducer is covered by a glass plate potted in silicone sealant. Tilt calibration tests have shown that the output of the SIMM transducer falls off at large angles of incidence. This is due primarily to the glass cover plate and is normally termed "cosine error".

The measured cosine response of the SIMM transducer was input into a computer simulation model to predict the effect of this error on the daily total insolation throughout the year (Table 1). Experimental data presented later in this report indicates that the summer errors are less than those predicted by the model.

TABLE 1.
CALCULATED EFFECT OF COSINE ERROR (%)

MONTH	CLEAR DAY	AVERAGE DAY
DEC	-2	-2
JAN NOV	-3	-2
FEB OCT	-4	-3
MAR SEP	-4	-3
APR AUG	-6	-4
MAY JUL	-8	-5
JUN	-8	-5

4. CLEAR DAY METHOD

All SIMM transducers are calibrated before installation. The reference instruments have included Kipp pyranometers, Li-Cor radiometers and a NOAA calibrated SIMM transducer. To allow for drift and aging, which may occur while the instrument is on site, we make use of a clear day correction technique similar to the methods used to correct the SOLMET data base.

The essence of our clear day procedure is to compare the measured noon flux to a value predicted by a theoretical clear day model. We have used the ASHRAE model and a model provided by Douglas Hoyt of NOAA (3). As part of our data reduction procedure we pick off the noon maximum on all clear days and compute a theoretical value for that same day. If there is a consistent difference of more than a few percent, the experimental data for that period is all scaled to match the theoretical value. Figure 3 shows a graph of experimental and theoretical clear day values for two stations for 1978.

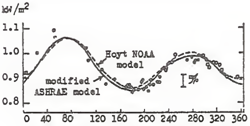


Fig.3a. Great Falls data for 1978 showing two clear-day models with data

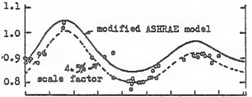


Fig.3b. Glendive data for 1978 illustrating use of scale factor

Experimental clear day maximums from an Eppley PSP (used in the National Solar Data Network) are compared to the theoretical Hoyt values in Table 2. The measured maximums fluctuate about the theoretical maximum. This could be due to fluctuations in the atmosphere and errors due to temperature effects, calibration and dirt on the instrument. The absolute value of this fluctuation for 1980 in Billings, MT average 2.3%. SIMM data are typically matched to the Hoyt model to within 3% annual average deviation (1, 2). This data thus supports the clear day method used in the SIMM network.

TABLE 2.
CLEAR DAY, NOON MAX, (kW-m^2), BILLINGS 1980

DAY	HOYT NOAA	NSDN (PSP)	FOWLKES (SIMM)
6	0.92	0.98	0.98
19	0.95	0.96	1.00
20	0.95	1.01	1.01
28	0.98	1.07	1.01
29	0.98	1.17	1.00
54	1.06	1.04	1.01
55	1.06	1.07	1.07
86	1.08	1.07	1.05
95	1.05	1.03	1.03
97	1.05	1.05	1.00
104	1.02	1.02	1.00
105	1.02	0.97	0.98
107	1.01	1.00	1.01
108	1.01	1.00	0.99
111	1.00	0.96	0.99
117	0.98	0.95	0.98
118	0.97	0.93	0.95
127	0.94	0.90	0.92
128	0.94	0.92	0.94
142	0.89	0.84	0.90
143	0.89	0.86	0.90
145	0.88	0.86	0.92
161	0.86	0.84	0.83
165	0.85	0.83	0.85
174	0.85	0.82	0.83
177	0.85	0.84	0.83
178	0.85	0.84	0.84
179	0.85	0.86	0.85
180	0.85	0.86	0.87

5. NATIONAL SOLAR DATA NETWORK COMPARISON

The Billings Shipping solar system in Billings, Montana was instrumented three years ago for performance monitoring as part of The National Solar Data Network (NSDN). Global insolation is measured here by an Eppley PSP pyranometer tilted at 50°. Daily totals and maximums are reported each month in Environmental Data for Sites in the National Solar Data Network (4).

During 1980 there were 337 days of simultaneous data from both the NSDN (Eppley PSP) and the SIMM transducer at Billings High School. The NSDN 50° tilt data was converted to a 60° tilt using the ratio of ASHRAE clear day totals. This simplified method would tend to over-correct the NSDN data by a few percent in the summer. Since the correction itself averages only about ± 3%, the error introduced is not large (5).

A scatter plot of daily total insolation for SIMM vs. NSDN for 1980 is shown in Figure 4. For 337 common data days, the linear correlation coefficient was 0.990. There are about a dozen points that are scattered. These discrepancies probably occurred on days when

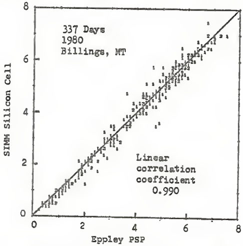


Fig. 4. Scatter plot, daily totals, kWh-m^2

TABLE 3.
DAILY TOTALS, (kW-m^2), BILLINGS, NOV. 1980

DAY	NSDN (PSP)	FOWLKES SIMM	NSDN LESS SIMM
1	2.59	2.66	-.07
2	2.18	2.13	.05
3	5.70	5.72	-.02
4	1.92	1.59	.33
5	6.07	6.16	-.09
6	1.51	1.25	.26
7	1.06	1.00	.06
8	4.41	4.78	-.37
9	1.06	1.06	.00
10	2.42	2.47	-.05
11	1.23	1.19	.04
12	0.65	0.63	.02
13	0.87	0.47	.40
14	5.27	5.06	.21
15	5.80	5.91	-.11
16	5.74	5.84	-.11
17	5.87	5.81	.06
18	2.92	2.84	.08
19	1.65	1.41	.25
20	3.76	3.84	-.08
21	1.82	1.84	-.03
22	0.58	0.50	.08
23	5.75	5.63	.13
24	2.28	2.22	.06
25	0.85	0.53	.31
26	5.17	4.63	.55
27	0.94	0.81	.13
28	5.80	5.31	.48
29	1.82	1.72	.11
30	0.39	0.38	.02
AVG	2.94	2.85	3.07%

snow or frost covered one transducer part of that day. Neither instrument is regularly cleaned or cleared of snow. The remaining scatter is primarily due to differences in spectral response, calibration error, cosine response and temperature coefficients (annual temperature extremes span over 70° C).

The daily totals for the month of November, 1980 are shown in Table 3. The daily average insolation for November for the SIMM instrument is 3.07% less than the NSIN instrument. This difference closely corresponds to the -3% error predicted for this month due to the low cosine response of the SIMM transducer.

The average daily totals for each instrument are shown for each month in 1980 in Table 4. The SIMM instrument is normally lower by a few percent, which is probably due to cosine error. (The December average is faulted because the SIMM instrument was not recording data during a week with several clear days.)

TABLE 4.
MONTHLY AVERAGE DAILY TOTAL (kW-m^{2})

MONTH	NSIN (PSP)	FOWLKES SIMM
JAN	3.13	3.29
FEB	3.29	3.29
MAR	4.14	4.01
APR	5.23	5.18
MAY	4.77	4.74
JUN	4.84	4.82
JUL	5.25	5.15
AUG	4.75	4.73
SEP	4.80	4.72
OCT	*4.38	4.33
NOV	2.94	2.85
DEC	2.05	*1.88

*missing 8 to 10 days

6. SIDE BY SIDE COMPARISONS

Side by side comparisons were run for eight months during the winter of 1980 and spring of 1981 to compare (a) a Kipp pyranometer, (b) a Li-Cor 200S silicon cell radiometer, and (c) the SIMM silicon cell radiometer. All transducers were mounted at 0° azimuth and 60° tilt and connected to a microcomputer based data acquisition system (DAS). The DAS has a resolution of 12 bits, an accuracy of better than ± 0.5%; each transducer and the ambient air temperature were sampled once each second. These readings were averaged over 10 minute intervals and the average data stored on magnetic tapes. This data base consists of 15×10^6 side by side readings of each transducer.

Table 5 shows a typical portion of this data base condensed into daily total insolation. The Kipp pyranometer was recalibrated at the NOAA facility in 1979 and this calibration factor was used. The factory calibration supplied for the Li-Cor was used and the SIMM transducer was calibrated to the Kipp on a clear day near solar noon according to our standard procedure. No correction was made for ambient temperature, which varied between -18° C and +17° C during this period. The monthly totals of the Kipp and the Li-Cor agree to within ± 1% while the SIMM transducer is 3% below the Kipp. This lower reading agrees with the predictions of the cosine error model discussed previously (Table 1).

TABLE 5.
BOZEMAN DAILY TOTALS (kWh-m^{2})
NOVEMBER, 1980

DAY	KIPP	LI-COR	SIMM
1	2.80	2.84	2.72
2	1.95	1.94	1.88
3	1.01	0.99	0.93
4	2.04	2.07	1.96
7	0.42	0.44	0.39
8	4.21	4.22	4.13
9	1.39	1.39	1.31
10	1.40	1.32	1.30
11	0.54	0.55	0.53
12	1.14	1.15	1.12
13	5.67	5.62	5.44
14	*5.33	6.60	6.36
15	6.68	6.55	6.38
16	6.62	6.61	6.43
17	4.13	4.40	4.24
18	1.10	1.03	1.05
19	0.93	0.89	0.86
20	3.83	3.77	3.68
21	3.04	3.02	3.00
22	0.73	0.68	0.66
23	5.43	5.40	5.28
24	3.71	3.61	3.54
25	0.71	0.64	0.63
26	4.44	4.43	4.28
27	1.74	1.66	1.66
29	2.01	1.94	1.93
30	1.54	1.45	1.44
AVG	2.66	2.64	2.57

*Frost

The instantaneous readings of the three transducers during mid-day in clear weather were always within a ± 5% band and often were within ± 1%. The Kipp and the Li-Cor were typically within ± 0.01 kW-m^{2} for the entire day, while the SIMM transducer's output would typically be 0.05 kW-m^{2} low in early morning and late afternoon (the cosine error).

7. SIMM NETWORK RELIABILITY

Each summer a technician visits all 30 stations to check the transducer mounting and the condition of the wiring and the strip chart recorder. If the system breaks down during the year the recorder and/or transducer are sent to us by the volunteer. We repair or replace the unit, test it, and send it back.

During the period between January, 1977 and December, 1980, there were 38,956 possible station data-days. We recorded 32,425 data-days, or 83% of the total. The 17% lost data was primarily due to recorders running out of paper (mostly during the summer months). During four years of operation two recorders were stolen, two transducers were vandalized, six motors burned out and there were about two dozen instances of miscellaneous mechanical or electrical failure. Data was lost several times when wires were cut or power was turned off during remodeling work at the school. Some data has been lost in the mail and in two instances strip charts were destroyed by a janitor's floor polisher. Some suspicious data has been rejected after arriving at the office.

8. CONCLUSIONS

- The clear day correction method provides an economical way to maintain the calibration of the network. Current comparison data indicated that this correction puts the data into a ± 5% accuracy band.

- The data recovery of 83% would be difficult to improve in this volunteer operated network. Missing data is not too important due to the high density of the 30 measuring stations.

- Extensive comparison data shows that errors due to spectral and temperature effects are well within the ± 5% error band. The most serious fault with the SIMM transducer is the poor cosine response which produces a systematic error of about -3% during the heating season.

- This data base has been made available to the public along with supplementary material in an effort to improve the quality of solar design in Montana.

- Measuring insolation on a 60° tilted surface reduces the net error in the data when used for solar design.

9. ACKNOWLEDGEMENTS

This measurement program is funded by a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. This program derives funds from a severence tax on coal mined in Montana. The support and advice of John Orndorff, Jeannie Thurston and Georgia Brenedal are acknowledged. The assistance of the volunteers at the measurement stations is crucial to the success of this program and their contributions are gratefully acknowledged.

Several members of the staff at Fowlkes Engineering have contributed to this solar measurement program and this paper. Sharon Kleingartner and Pat Sullivan have carefully logged and organized strip chart records for over 40,000 data-days. Sharon is acknowledged for her important role in entering the data into the computer for processing. Carlos Lozano has contributed to this paper by writing numerous computer programs to analyze the data. Jody Martinson typed this paper and made editorial corrections.

10. REFERENCES

(1) Fowlkes, Charless W., "Operation and Results of a 30-Station Solar Radiation Network in Montana", Proceedings of the 1980 Annual Meeting, AS/ISES. Phoenix, AZ (1980).

(2) Fowlkes, Charless W., Montana Solar Data Manual, available from Montana Department of Natural Resources & Conservation, Alternative Renewable Energy Sources Program, 32 South Ewing, Helena, MT 59620 (1979).

(3) Hoyt, Douglas V., "A Model for the Calculation of Solar Global Insolation", Solar Energy, Vol. 21, No. 1 (1978).

(4) Environmental Data for Sites in the National Solar Data Network (monthly), DOE, NATIONAL SOLAR DATA PROGRAM, Solar/0010-80.

(5) ASHRAE HANDBOOK OF FUNDAMENTALS, New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers (1972).

Progress in Solar Energy Copyright 1982 by American Section of the International Solar Energy Society, Inc Printed in U S A

0731-860X/82/0501-1283$3 00

MEASUREMENTS OF SOLAR RADIATION IN THE UPPER HEMISPHERE USING AN ARTICULATED RADIOMETER

Charless W. Fowlkes, Ph.D., P.E.
Fowlkes Engineering
31 Gardner Park Drive
Bozeman, Montana 59715

ABSTRACT

The goal of this project is to measure solar radiation (quasi) simultaneously at 144 positions of tilt and azimuth in the upper hemisphere. The apparatus consists of a solar radiometer fixed to an articulating mechanism driven by stepping motors which are controlled by a low-cost microcomputer. At each 15° increment of altitude and azimuth, the radiant flux is sensed by the radiometer and the resulting electrical output digitized and stored in the computer. The upper hemisphere is scanned once each 30 seconds. At the end of each hour, the solar radiation measured in each direction is averaged and the result stored on magnetic tape. The data base consists of hourly averages of the solar flux on each of 144 planes. This paper describes the experimental apparatus and presents preliminary data.

1.0 INTRODUCTION

The majority of available solar radiation data consists of global radiation measured on a horizontal plane. A horizontal orientation is normally selected by meteorologists because they are primarily interested in a "horizontal" solar collector, the earth. A solar designer, however, will normally tilt the collector plane between 40 and 90° up from the horizontal to increase the average radiant flux density intercepted by the collector. To meet the needs of solar designers, a number of empirical rules have devised relating solar flux on a horizontal surface to the solar flux on a tilted surface. A complete review of the literature of "tilt correlation" studies is beyond the scope of this paper, but eamples of important work in this area are included in References (1), (2), (3), and (4).

A comparison of several popular tilt correlation algorithms was initiated at the Solar Energy Research Institute (SERI) in 1978. This comparison revealed discrepancies among the various algorithms which stimulated the initiation of experimental measurements of insolation on tilted surfaces (5). Insolation data has subsequently been collected at the SERI field site from an apparatus which consists of a series of pyranometers facing south and tilted at angles between 90 and 0° at 10° increments. This array of measuring instruments included Eppley PSP pyranometers and Li-Cor LI-200S silicon cell radiometers mounted side by side. Data from these experiments will probably be published during the coming year. Data from simultaneous measurements on six planes is given in Reference (7).

Silicon cells have a non-uniform spectral response which will produce errors in the indicated radiant flux in some situations (6). Preliminary data from the SERI experiment showed close agreement between the global solar radiation indicated by the pyranometers and the solar radiation indicated by the silicon cell based radiometers (5), (8). Our data from extensive side-by-side pyranometer and silicon cell radiometer tests have also shown good overall agreement (9). Since the silicon cell radiometer exhibits both adequate accuracy and time response, it appeared feasible to use this transducer in the scanning mode to gather insolation data (quasi) simultaneously at a large number of angles of incidence.

2.0 SCANNER APPARATUS

Figure 1 shows a schematic of the overall apparatus. A silicon cell radiometer is attached to a stepping motor which will adjust its altitude. This assembly, in turn, is mounted on a second stepping motor with a vertical axis which can adjust the azimuth of the assembly. Both stepping motors are connected to appropriate drive electronics which are, in turn, interfaced to a microcomputer. The altitude and azimuth of the solar radiometer can now be adjusted in response to commands issued by the microcomputer. The output of the solar radiometer is connected to an A/D converter (Figure 1)

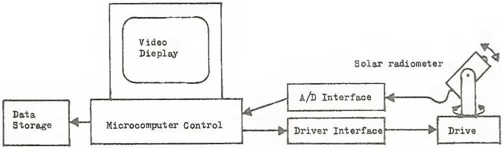


Fig. 1. Schematic diagram of computer control and interface.

which is interfaced to the microcomputer. This experimental arrangement allows the computer to move the sensor to a specified azimuth and altitude and to read the corresponding solar radiation.

The solar radiometer chosen for this experiment was a Li-Cor LI-200S. The mechanical arrangement is shown in greater detail in the diagram in Figure 2. In this diagram, the radiometer is mounted to the shaft of the altitude stepping motor. This assembly, in turn, is mounted to the shaft of the azimuth stepping motor. The altitude stepping motor can rotate through 180° in 7.5° increments (from a vertical tilt through horizontal to a vertical tilt in the opposite direction), Figure 2. The azimuth motor can rotate through >180° in 15° increments.

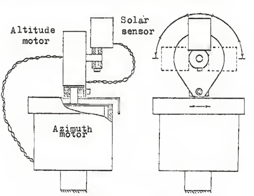


Fig. 2. Details of actuator.

3.0 COMPUTER INTERFACE

The microcomputer used with this apparatus is a Radio Shack TRS-80 with 16K memory and Level II BASIC. This machine was chosen because we have used several TRS-80's for data loggers while monitoring the performance of solar heated buildings, and because we had an extra one on hand. The TRS-80 was connected to an interface which incorporated an 8-channel, 8-bit A/D converter, an 8-bit digital output port and an 8-bit digital input port. All ports can be controlled by commands from BASIC. Four bits of the output port were used to control the rotation of the altitude and azimuth motors (two bits each). Both the azimuth and altitude motors were fitted with a limit switch which was actuated when the sensor was in the "home" position. Two bits of the input port were used to sense these switches. A real time clock based on a quartz oscillator was monitored through another bit on the input port. This input allowed the system to keep track of time.

Three of the eight A/D converter inputs were used for this experiment. The first input was used to digitize the signal from the scanning Li-Cor radiometer. The second analog input monitored the output of an Eppley PSP pyranometer mounted at a 60° tilt facing

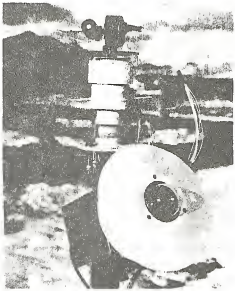


Fig. 3. Scanning radiometer and reference PSP.

due south. The third analog channel monitored the output of an Analog Devices AD590 temperature transducer. Signal conditioning circuits were fabricated for each of the transducers which amplified and/or offset the transducer signal to utilize the full 5 V range of the A/D converter. The completed scanning radiometer and the reference Eppley PSP are shown in Figure 3. The computer, interface, stepping motor driver and cassette data storage are shown in Figure 4.

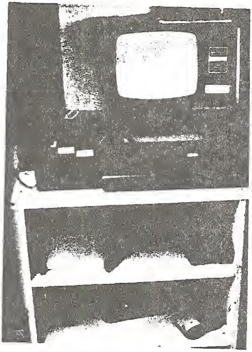


Fig. 4. Computer and interface.

4.0 ACCURACY OF SYSTEM

The stepping motors used in this system are relatively low cost and are manufactured by North American Phillips. They are designed to move 7.5° or 15° per step. The nominal accuracy of these motors is 5% or 0.75°. The outputs of the solar transducers were amplified using a two-stage operational amplifier circuit having a gain of about 370. The temperature sensitivity of the amplifier circuits and the analog digital converter were tested by applying a fixed input and observing the output while the temperature of the entire electronic assembly was forced through a 30° temperature difference. These tests showed that the outputs were within ±0.5 bit for a temperature change of 30° C. The maximum resolution of the 8-bit converter is one part in 256, or about 0.5%. Since the electronics are normally located within a "human" condition space, this change in sensitivity was judged negligible.

The indexing accuracy of the altitude motor was tested on a clear day when the solar radiation was practically constant over small time intervals. The system was programmed to scan through 13 altitude positions and then return without changing azimuth. The solar radiation was measured at each position. The results of this test showed that 95% of the readings of solar radiation were within ±0.5 bit. The results were the same for several values of azimuth, implying that the altitude indexing errors were within the resolution of the A/D converter.

When the solar transducer is at an incident angle of 75°, an error of ±1° would produce a solar radiation variation of ±3 bits. The measured experimental variations of ±0.5 bit agree closely with the published indexing accuracy of the motor, which is ±0.4°. A similar test on the azimuth motor showed a reproducibility of ±1 bit. This value corresponds to the nominal accuracy of the motor, which is 0.75°. The combined indexing errors appear less than ±1°.

The overall electrical noise in the assembled system was tested by programming the transducer so that it remained at a fixed angle on a clear day when the solar radiation was nominally constant. The output variation of the solar transducer as indicated by the entire system was constant within ±0.75 bits.

The test results show that errors in reading the solar radiation with this apparatus due to errors in altitude, azimuth, noise and temperature drift are, on the average, within ±1 bit. On a clear day, the solar radiation indicated by the radiometer when it is pointed directly at the sun is nearly 200 bits. These accuracy tests indicate that errors due to all sources are of the order of 1%.

The references quoted previously show that the silicon cell radiometer is typically within a few percent of the precision pyranometer and often within 1% of the precision pyranometer. The total errors incurred in this experimental apparatus are, therefore, within the uncertainty band of the silicon cell radiometer.

5.0 OPERATION AND TEST PROCEDURE

The scan routine is depicted in Figure 5. A single scan begins with the axis of the transducer horizontal and pointed due east. The transducer sequentially increments 15° in altitude until it is horizontal and facing due west. At this point, the azimuth increments 15° towards the north and the transducer returns in 15° increments until the axis is horizontal and facing south of due

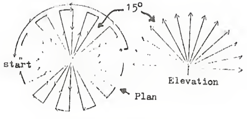


Fig. 5. Geometry of scan routine.

east by 15°. This procedure continues until the transducer has pointed at all directions in the upper hemisphere on 15° increments. The transducer then returns to the home position of due east. The entire scan is completed in less than 30 seconds. (The scanner can be driven at over 2x this rate but the indexing errors will increase by 1%.)

The transducer goes through a horizontal position on each 180° scan of the azimuth angles. If the solar radiation is uniform throughout the period of the scan, then the horizontal readings of each azimuth scan will agree to within ±1 bit. The multiple readings of the horizontal insolation allow a continuous accuracy check on the indexing and conversion of the apparatus. The altitude and azimuth limit switches are checked during each scan. If an indexing error is detected, the data from that scan is ignored and the sensor is automatically repositioned by the computer.

At the end of each scan, the temperature and the output of the fixed, Eppley PSP is read. The PSP is mounted at an angle of 60° up from horizontal, facing true south. This angle corresponds to one of the 156 positions of the scanning Li-Cor radiometer. Comparison of the outputs of the two instruments at this angle allow a further check on the accuracy and validity of the data.

At the end of the hour, the average radiation at each of the 156 scanning positions is calculated. The average reading of the fixed PSP pyranometer and the ambient temperature are also calculated. These results are saved on cassette tape along with the Julian day number and the hour of the day. The total data base each hour consists of 160 8-bit bytes. The data tapes generated by the Radio Shack TRS-80 microcomputer are subsequently read by a North Star Horizon microcomputer and the data transferred to floppy diskette. These data files are stored as 8-bit bytes for subsequent processing.

The system is programmed to scan and save data for all daylight hours. At night, the system is put into a slower scanning mode, and no data is saved. This keeps the motors warm and prevents snow from accumulating on the Li-Cor, Figure 6.

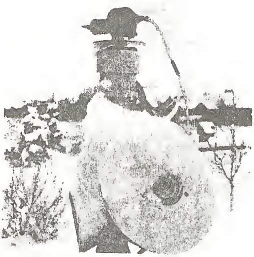


Fig. 6. Effect of snow.

6.0 SAMPLE DATA

A video display of the raw data resulting from one scan of the hemisphere is shown in Figure 7. The matrix of hourly average data near noon on February 24 is shown in Table 1. This day was clear and the ground was covered with snow. The format of this Table corresponds to the sequential azimuth and altitude indexing of the sensor. This output is somewhat "warped" in space as compared to the geometry of the readings themselves. The sun was almost due south during this hour so the values are nearly symmetric about the 0° azimuth row.

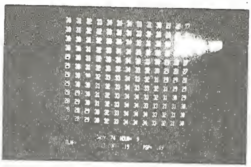


Fig. 7. Display of output during a single scan on a cloudy day.

Table 2 shows the data from Table 1 normalized to the radiation measured at a 60° south-facing tilt. During the past five years, we have measured insolation on a 60° south-facing tilt at 30 locations in Montana (over 45,000 data days), (10). We hope that data from this scanning experiment will help

TABLE 1
MATRIX OF HOURLY AVERAGE DATA ON A CLEAR DAY NEAR SOLAR NOON, $kW\text{-}m^{-2}$

Altitude,deg.

Azimuth,deg.	0	15	30	45	60	75	90	105	120	135	150	165	180
-90	0.40	0.47	0.54	0.59	0.63	0.64	0.64	0.61	0.56	0.48	0.40	0.32	0.31
-75	0.59	0.66	0.71	0.73	0.72	0.69	0.64	0.56	0.45	0.34	0.24	0.26	0.31
-60	0.78	0.84	0.88	0.87	0.82	0.75	0.64	0.52	0.36	0.21	0.20	0.26	0.31
-45	0.95	1.01	1.02	0.98	0.90	0.78	0.64	0.47	0.29	0.15	0.20	0.26	0.31
-30	1.08	1.13	1.13	1.07	0.97	0.84	0.65	0.44	0.24	0.15	0.20	0.26	0.31
-15	1.16	1.20	1.19	1.12	1.00	0.84	0.64	0.42	0.19	0.15	0.20	0.26	0.31
(S) 0	1.18	1.22	1.21	1.14	1.02	0.85	0.65	0.42	0.19	0.15	0.19	0.25	0.30
15	1.15	1.19	1.18	1.11	1.00	0.84	0.64	0.42	0.19	0.14	0.19	0.25	0.30
30	1.07	1.12	1.11	1.07	0.96	0.82	0.65	0.46	0.26	0.14	0.19	0.24	0.30
45	0.95	1.00	1.01	0.98	0.90	0.78	0.65	0.48	0.30	0.15	0.19	0.24	0.30
60	0.78	0.84	0.87	0.86	0.82	0.75	0.65	0.53	0.39	0.25	0.19	0.24	0.29
75	0.61	0.67	0.72	0.74	0.73	0.70	0.65	0.57	0.47	0.36	0.26	0.24	0.29

TABLE 2
HOURLY DATA NORMALIZED TO 60° TILT (30° altitude) AND 0°AZIMUTH, $kW\text{-}m^{-2}$

Altitude,deg.

Azimuth,deg.	0	15	30	45	60	75	90	105	120	135	150	165	180
-90	0.33	0.39	0.45	0.49	0.52	0.53	0.53	0.50	0.46	0.40	0.33	0.26	0.26
-75	0.49	0.55	0.59	0.60	0.60	0.57	0.53	0.46	0.37	0.28	0.20	0.21	0.26
-60	0.64	0.69	0.73	0.72	0.68	0.62	0.53	0.43	0.30	0.17	0.17	0.21	0.26
-45	0.79	0.83	0.84	0.81	0.74	0.64	0.53	0.39	0.24	0.12	0.17	0.21	0.26
-30	0.89	0.93	0.93	0.88	0.81	0.69	0.54	0.36	0.20	0.12	0.17	0.21	0.26
-15	0.96	0.99	0.98	0.93	0.83	0.69	0.53	0.35	0.16	0.12	0.17	0.21	0.26
(S) 0	0.98	1.01	$\boxed{1.00}$	0.94	0.84	0.70	0.54	0.35	0.16	0.12	0.16	0.21	0.25
15	0.95	0.98	0.98	0.92	0.83	0.69	0.53	0.35	0.16	0.12	0.16	0.21	0.25
30	0.88	0.93	0.92	0.88	0.79	0.68	0.54	0.38	0.21	0.12	0.16	0.20	0.25
45	0.79	0.83	0.83	0.81	0.74	0.64	0.54	0.40	0.25	0.12	0.16	0.20	0.25
60	0.64	0.70	0.72	0.71	0.68	0.62	0.54	0.44	0.32	0.21	0.16	0.20	0.24
75	0.50	0.55	0.60	0.61	0.60	0.58	0.54	0.47	0.39	0.30	0.21	0.20	0.24

establish empirical tilt correlation factors. These factors would greatly increase the utility of the existing 60° tilted data base.

As an aid toward visualizing the data, models have been constructed depicting the three-dimensional surface of the solar radiation. The photograph in Figure 8 shows a model of the solar radiation in the upper hemisphere at noon on a clear day (data from Table 1). The model clearly shows a large "bulge" in the direction of the sun. The intensity of the solar radiation drops off rapidly for northerly azimuths. The radiation reaches a minimum when the transducer is pointed approximately 45° above the horizon and due north. As the axis of the transducer approaches horizontal, additional radiation is recorded due to reflections from the snow. This reflection produces a "foot" on the model when the transducer points north.

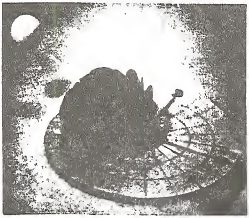


Fig. 8. Model of solar radiation in upper hemisphere at noon.

Figure 9 shows both the noon model and a morning model (9:30 a.m.). The average intensity of the radiation is less for the

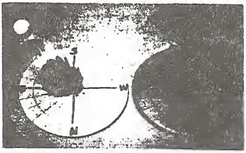


Fig. 9. Morning and noon models.

morning model but the shape is similar. This model also shows the "foot" due to back-reflected radiation from the snow covered surface.

7.0 CONCLUSIONS

(1) The results presented in this paper are preliminary. Nearly two months of satisfactory hourly data are currently on file.

(2) At the writing of this paper, the bugs in the apparatus have been resolved and data is being logged on a regular basis. Data will be collected for another three months under the present contract.

(3) Future work will include statistical analysis of the relationships between solar radiation on the various orientations as well as comparison with existing empirical relationships.

8.0 ACKNOWLEDGEMENTS

The work reported here was sponsored by a grant from the Department of Energy, Appropriate Technology Small Grants Program, Region VIII. These results are intended to amplify other measurements supported by the Montana Department of Natural Resources and Conservation, Renewable Energy Sources Program.

Ron Hulstrom and his group at SERI are acknowledged for their role in providing inspiration for this type of measurement program. Al Pershall designed and constructed many of the electronic interface circuits. Jody Martinson and Sharon Kleingartner contributed to the preparation of the final manuscript.

9.0 REFERENCES

(1) Liu, B.Y.H. and R.C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation", *Solar Energy*, Vol. 4, No. 3, pp. 1–19, 1960.

(2) Page, J.K., "The Estimation of Monthly Mean Values of Daily Total Short-wave Radiation on Vertical and Inclined Surfaces from Sunshine Records for Latitudes 40°N – 40°S.", *Proceedings of the UN Conference on New Sources of Energy*, 4, 378, 1964.

(3) Becker, C.F. and J.S. Boyd, "Solar Radiation Availability on Surfaces in the United States as Affected by Season, Orientation, Latitude, Altitude and Cloudiness," *Solar Energy Journal, Science & Engineering*, Vol. 1, January, 1957.

(4) Temps, R.C. and K.L. Coulson, "Solar Radiation Incident Upon Slopes of Different Orientations," *Solar Energy*, Vol. 19, pp. 179–184, 1977.

(5) Hulstrom, Roland L., "Insolation Models, Data and Algorithms", Solar Energy Research Institute, SERI/TR-36-110.

(6) Dirmhirn, Inge, "On the Use of Silicon Cells in Meteorological Radiation Studies", *Journal of Applied Meteorology*, Vol. 7, No. 4, 1968.

(7) Healey, James, Robin Near and John Boston, "Solar Irradiance Data for the Passive Designer", *Proceedings of the Fifth National Passive Solar Conference*, 1980.

(8) Stoffel, Tom, SERI, private communications, August 1981.

(9) Fowlkes, Charless W., "Controlling the Accuracy of Solar Radiation Data From a Low Cost, 30 Station Network", *Proceedings of the Sixth National Passive Solar Conference*, September, 1981.

(10) Fowlkes, Charless W., *Montana Solar Data Manual*, available from Montana Department of Natural Resources and Conservation, Helena, Montana, 59620, (1979).

Reprint from *PROCEEDINGS OF THE 1980 ANNUAL MEETING*
Published by American Section of the International Solar Energy Society, Inc.
205B McDowell Hall, University of Delaware, Newark, DE 19711.

OPERATION AND RESULTS OF A 30-STATION SOLAR RADIATION NETWORK IN MONTANA

Charles W. Fowlkes
Fowlkes Engineering
31 Gardner Park Drive
Bozeman, MT 59715

ABSTRACT

This paper describes the operation and results of a current state-supported program, Solar Insolation Measurement, Montana (SIMM). The goal of this program is to measure and document the solar insolation available at 30 locations within the state of Montana. To date, over 25,000 solar insolation data-days have been collected. A summary of most of this data is available to the public in the Montana Solar Data Manual, Fig. 1. (1)

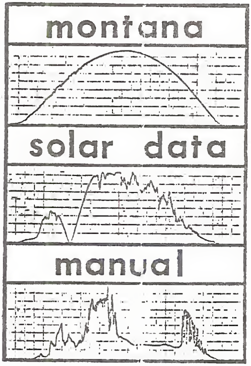
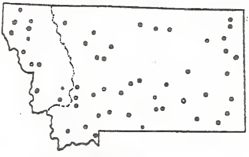


Fig. 1. Cover of Montana Solar Data Manual, illustrating solar insolation records (including eclipse on Feb. 26, 1979).

1. INTRODUCTION

Early in 1977 the SIMM program (Solar Insolation Measurement, Montana) was initiated by Fowlkes Engineering under a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. Twenty instruments to measure solar radiation were sited across Montana during 1977 and an additional ten instruments were sited early in 1978. In addition to the thirty stations having continuous insolation recorders there are currently twenty-five stations which report the readings of manual instruments, Fig. 2.



● Continuous Data Recording Station

○ Manual Data Station

Fig. 2. Montana Solar Insolation Measurement Network

All of the instruments are located in public high schools. At each school there is a volunteer, usually a science teacher, who is responsible for the instrument. The volunteer periodically replaces the chart paper in the recorder and mails the completed strip charts to our office for processing. The total time required for the volunteer to do these tasks usually amounts to less than five hours each year.

The solar insolation strip chart recorders are often located in a laboratory, office, or classroom where they can be seen by the students. Some teachers make specific use of the insolation records in their classes.

All high schools participating in the SIMM program receive a copy of The Handbook of Solar Energy Experiments and a manual solar insolation meter. This Handbook was writte by the author of this paper as an integral part of the insolation measurement program. The 80 page Handbook contains a review of solar basics and ten outlined experiments ranging from insolation measurement to testing a solar collector.

2. INSOLATION ON A TILTED SURFACE

Meteorological insolation data is usually recorded on a horizontal surface due, in part, to the fact that the solar collector of interest to meteorologists is the horizontal surface of the earth. For northern U.S. latitudes the solar designer wall normally tilt the collector plane between 45° and 90° up from the horizontal to increase the average radiant flux density intercepted by the collector. Procedures exist for estimating the insolation on a tilted surface given the measured insolation on a horizontal surface. However, the net uncertainties of these estimates in northern U.S. latitudes during the winter will be around ± 20%. Some uncertainties arise from the pyranometer errors at low solar altitudes. Additional uncertainties exist due to reflected radiation from snow-covered ground which will be intercepted by steep solar collectors but will not be intercepted by a horizontal radiation transducer.

Since the goal of the SIMM program is to develop a solar insolation data base for designing solar conversion devices we measure insolation on a surface tilted 60° up from horizontal and facing due south. The transducer hence becomes a model of a typical solar collector which might be used at this latitude to collect heat in the winter. The resulting 60° solar radiation data can often be used directly or can be transformed to neighboring tilt angles with relatively small increases in uncertainty. The effects of snow and dirt on a collector are approximately modeled by this transducer orientation and are an integral part of the insolation data.

3. INSTRUMENTATION

The solar insolation is sensed by a silicon cell mounted in an 8cm square aluminum plate and covered with glass. The transducer is attached to a bracket outside the building and a wire runs to a strip chart recorder located inside the building. We fabricated all the transducers used in this program.

Silicon cell characteristics relating to solar flux measurement are well documented in the literature and several commercial silicon cell instruments are available (2). Characteristics causing departures from pyranometer readings are due to spectral response, temperature changes and cosine response. The spectral response will cause the silicon cell to read measurably higher on cloudy days. The instruments used in this program, for example, will read about 0.015 kWh/m^2 high under conditions of 80% beam attenuation due to clouds. The effect of this spectral error on the monthly average, daily total energy density is typically reduces to less than 3%. This reduced error is due to the relatively low energy density on cloud days. Cosine errors are minimized due to the tilted orientation.

The electrical circuit used is sensitive to changes in lead resistance. This factor has probably been a primary source of error in this measurement program. Resistance variations are usually due to improperly soldered lead wire connections. The gradually increasing contact resistance leads to a gradual reduction in sensitivity of the instrument. In a few cases this problem has been responsible for temporary errors of 10 and 20%. We are currently inspecting and servicing the instruments at all 30 stations.

4. DATA REDUCTION

Strip chart data is processed by tracing the curves on a digitizer platen connected to a microcomputer, Fig. 3. The resolution of the platen is 0.1 mm and each curve is represented by 200 to 400 coordinates. The reading error due to resolution is less than .1%. The primary source of data reduction error is the repeatability of the curve tracing itself. On clear days, where the curve is a well defined line, the reproducibility averages 1%. On cloudy days the reproducibility can reach 5 to 20%. This is due to the fast response of the silicon cell which produces a very rough, jagged curve on some cloudy days, Fig. 1.

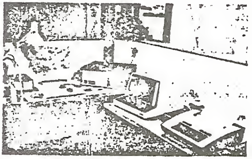


Fig. 3 Computer system used to read strip-charts

During the last year reproducibility tests have been run on over 800 data days (4% of our total data base). The reproducibility of the monthly average, daily total energy density averages better than ± 2%. These monthly values often reproduce within 1% due to the compensation of positive and negative errors when averaged.

The processed data from each day consists of day number, total energy density, day length, noon maximum intensity (if day was clear), intensity spectrum, half-hour average solar intensities, and a fault code (specifying lost or suspect data). The total energy is stored in 2 (8 bit) bytes and thus has a maximum resolution of 1 part in 512. All other non-integer quantities are rounded to integers and stored in a single byte in the file (maximum resolution 1 part in 256). The maximum loss of precision in this data due to rounding off is 0.5%.

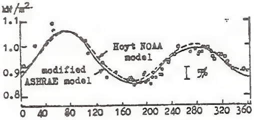
The data are stored on hard-sectored, 5¼ inch magnetic diskettes using the North Star Disc Operating System (a popular microcomputer format). Each single-density diskette contains 3 station-years of solar data. This data has been used by Fowlkes Engineering as input to solar heating simulation models. Copies of these diskettes can be supplied at nominal cost for users wanting to implement their own simulation programs.

5. DATA ACCURACY, CLEAR DAY METHOD

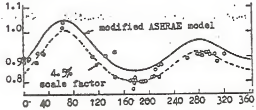
All transducers are calibrated before installation to establish a nominal calibration factor. The reference instruments have included Kipp pyranometers, Li-Cor radiometers and one of our transducers which was calibrated by NOAA. This provides an initial reference point but does not allow for the effects of drift and aging, which may occur while the instrument is on site. For long term control of accuracy we make use of a clear day technique similar to the methods used to adjust the SOLMET data base (3).

The essence of our clear day procedures is to compare the measured radiant flux at noon to a value predicted by a theoretical clear day model. We have studied two clear day models. The first model was provided by Douglas Hoyt (4) and the second model was based on the ASHRAE equations with a clearness modification to account for altitude.

As part of our data reduction procedures we pick off the noon maximum on all clear days and this value is stored in the data file. Before summarizing the annual data we have a program that scans all clear days and computes a theoretical value for that same day. If there is a discrepancy of more than a few percent, the experimental data is scaled to agree with the theoretical value. Figure 4 shows a comparison of theoretical and experimental clear day values for two stations in 1978. Figure 4 (b) shows data that was subsequently scaled for a better fit. We feel that this procedure insures that our data base does not contain significant or large errors. After scaling most of the stations match the theoretical clear day values to withing ± 2% or better.



(a) Gt. Falls data for 1978 showing two clear-day models with data



(b) Glendive data for 1978 illustrating use of scale factor

Fig. 4 Comparison of clear day experimental and theoretical values

6. DATA OUTPUT

The solar insolation data from this program has been summarized in the Montana Solar Data Manual. The first edition of this manual was distributed to libraries, extension services, engineers, and architects in the summer of 1979. An updated edition will be distributed in 1980. The new manual includes three years of solar insolation data in tables of weekly and monthly averages of daily totals. Also included are tables of the frequency of occurance of cloudy days and a reproduction of climatological data from NWS records. The manual includes a discussion of solar heating design methods, economic analysis, a list of references, conversion tables and a discussion of the accuracy of the solar data. The manual contains about 200 pages of information and is available from the state agency at no cost.

The average intensity spectrum is also presented as a percentage of the daily total energy density which occured at radiation intensities above 12 threshold values ranging from 0.1 to 1.2 kW/m².

Figure 5 reproduces a page of weekly average data from the Montana Solar Data Manual for Helena, Montana during 1978. The first column lists the starting date for the week and the second column lists the average daily total energy density, kW-hr/m²-day, during that week. The next twelve columns list the average spectrum during the week. Similarly, more compact tables listing monthly averages are also included in the Manual. Parentheses around the daily averages denote that at least one day of data was missing during the averaging period.

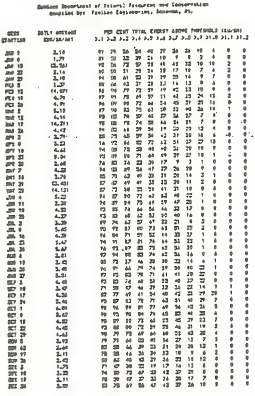


Fig. 5 Sample solar data from manual

The current Manual contains solar data from the first three years of the measurement program, 1977, 1978 and 1979. These measurements are being continued through the next year and the Data Manual will be updated at that time. If funds are available, this program will be continued to a point where long-term average insolation data can be reliably documented.

7. ACKNOWLEDGEMENTS

This measurement program is funded by a grant from the Alternative Renewable Energy Sources Program of the Montana Department of Natural Resources and Conservation. The support and advice of John Orndorff, Jim Iversen, Kitty Kvinge and Dana Gund[illegible] are acknowledged. The assistance of th[illegible]nteers at the measurement stations is crucial to the success of this program and their contributions are gratefully acknowledged.

Several members of the staff at Fowlkes Engineering have contributed to this solar measurement program and this paper. Pat Sullivan has carefully logged and organized strip chart records for over 25,000 data days. Sharon Kleingartner is acknowledged for her important role in entering the data into the computer for processing. Sharon also typed this paper and made editorial corrections.

8. REFERENCES

(1) Fowlkes, Charlese W., Montana Solar Data Manual, available from Montana Dept. of Natural Resources & Conservation, Alternative Renewable Energy Sources Program, 32 S. Ewing, Helena, MT 59601, 1979

(2) Selcuk, K. and Yellott, J. I., "Measurement of Direct, Diffuse, and Total Solar Radiation with Silicon Photovoltaic Cells", Solar Energy, Vol. 6, No. 4 (1962)

(3) U.S. Dept. of Energy-Div. of Solar Technology, "Hourly Solar Radiation-Surface Meteorological Observations", SOLMET Final Report, Vol.1 (1979)

(4) Hoyt, Douglas V., "A Model for the Calculation of Solar Global Insolation", Solar Energy, Vol. 21, No. 1 (1978)

16 copies of this public document were published at an estimated cost of $6.75 per copy, for a total cost of $108.00, which includes $108.00 for printing and $.00 for distribution.